

# **SOUTH BATTERY PARK CITY RESILIENCY PROJECT**

## **Coastal Modeling Study**

**FINAL**

**Prepared for: Battery Park City Authority**

**Prepared by:  
AECOM**

**April 27, 2022**

**TABLE OF CONTENTS**

<b>1.0</b>	<b>INTRODUCTION.....</b>	<b>1</b>
1.1	Project Area .....	1
1.2	Objectives and Scope of Work.....	2
<b>2.0</b>	<b>DEVELOPMENT OF COASTAL MODEL SYSTEM.....</b>	<b>2</b>
2.1	Regional Coastal Storm Surge Model ADCIRC.....	2
2.2	MIKE 21 Hydrodynamic FM Model .....	4
2.2.1	Topography and bathymetry .....	4
2.2.2	Model Domain and Mesh .....	5
2.2.3	Model Setup .....	9
2.3	ADCIRC and MIKE 21 HD FM Model Calibration and Validation .....	11
2.3.1	Model Calibration .....	11
2.3.2	Model Validation.....	18
2.4	Wave Models .....	23
2.4.1	MIKE 21 Spectral Wave Model .....	23
2.4.2	MIKE 3 Wave Model .....	24
<b>3.0</b>	<b>COASTAL FLOOD ASSESSMENT FOR EXISTING CONDITION.....</b>	<b>27</b>
3.1	Identification of Coastal Storm .....	27
3.2	Sea Level Rise .....	28
3.3	Coastal Flooding due to Coastal Storm Surges without Project.....	29
<b>4.0</b>	<b>COASTAL FLOOD ASSESSMENT OF PROPOSED RESISTANT ALIGNMENT.....</b>	<b>31</b>
4.1	Proposed Flood Resistant Alignment.....	31
4.2	Coastal Flooding due to Coastal Storm Surges (without SLR).....	32
4.3	Coastal Flooding due to Coastal Storm Surges (with SLR).....	32
4.4	Design Wave Condition .....	34
4.5	Design Wave Condition along Proposed Flood Resistant Alignment.....	39
4.6	Wave Runup and Overtopping - Transect Based (EurOtop) .....	40
<b>5.0</b>	<b>CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>0</b>
<b>6.0</b>	<b>REFERENCES.....</b>	<b>1</b>

Appendix A - SBPC Runup and Overtopping Calculations.xlsx

Appendix B - MIKE21SW\_wave\_extraction\_points.xlsx

Appendix C - Misc\_FIS\_profile\_slopes\_toe\_elevations.xlsx

**LIST OF TABLES**

Table 2-1 Summary of MIKE 21 HD FM Model Setup Parameters ..... 9

Table 2-2 Land Use Classifications and Manning’s Values for MIKE 21 Model ..... 10

Table 2-3 Summary statistics of the ADCIRC Model Calibration with Tide ..... 13

Table 2-4 Summary statistics of the ADCIRC Model Calibration with 1984 Nor’easter ..... 15

Table 2-5 Summary statistics of the MIKE 21 HD FM Model Calibration with Tide ..... 17

Table 2-6 Summary statistics of the MIKE 21 HD FM Model Calibration with 1984 Nor’easter ..... 18

Table 2-7 Summary Statistics of the ADCIRC Model Validation for Hurricane Sandy ..... 20

Table 2-8 Summary Statistics of the MIKE 21 HD FM Model Validation with Hurricane Sandy ..... 21

Table 3-1 Sea Level Rise Projections for New York City ..... 28

Table 4-1 Wave Runup and Overtopping under the 100-year Storm Condition with no SLR ..... 0

Table 4-2 Wave Runup and Overtopping under the 100-year Storm Condition with 2050 SLR ..... 0

**LIST OF FIGURES**

Figure 1-1 Project Study Area Map ..... 1

Figure 2-1 Numerical Grid and Model Domain of ADCIRC Model ..... 3

Figure 2-2 Extent of Topography and Bathymetry Surveys for Bathymetry Survey (top) and  
Topography Survey (bottom). ..... 5

Figure 2-3 Overview of MIKE 21 HD FM Model Domain and Boundary Locations ..... 6

Figure 2-4 Overview of MIKE 21 Hydrodynamic Model Mesh ..... 7

Figure 2-5 MIKE 21 Hydrodynamic Model: Refined Mesh at Project Site ..... 8

Figure 2-6 Manning’s M for MIKE 21 Hydrodynamic Model ..... 10

Figure 2-7 Location of the NOAA tidal stations at The Battery, Bergen Point, and Sandy Hook ..... 11

Figure 2-8 ADCIRC Model: Calibration with Tide at NOAA The Battery Tidal Station ..... 12

Figure 2-9 ADCIRC Model: Calibration with Tide at NOAA Bergen Point Tidal Station ..... 12

Figure 2-10 ADCIRC Model: Calibration with Tide at NOAA Sandy Hook Tidal Station ..... 13

Figure 2-11 ADCIRC Model: Calibration with 1984 Nor’easter at NOAA The Battery Tidal Station ..... 14

Figure 2-12 ADCIRC Model: Calibration with 1984 Nor’easter at NOAA Bergen Point Tidal Station ..... 14

Figure 2-13 ADCIRC Model: Calibration with 1984 Nor’easter at NOAA Sandy Hook Tidal Station ..... 14

Figure 2-14 Location of NOAA’s Battery Tide Station ..... 16

Figure 2-15 MIKE 21 HD FM Model: Calibration with Tide at NOAA’s Battery Station ..... 17

Figure 2-16 MIKE 21 HD FM Model: Calibration with 1984 Nor’easter at NOAA The Battery Station ..... 18

Figure 2-17 ADCIRC Model Validation at NOAA The Battery Tidal Station ..... 19

Figure 2-18 ADCIRC Model Validation at NOAA Bergen Point Tidal Station ..... 19

Figure 2-19 ADCIRC Model Validation at NOAA Sandy Hook Tidal Station ..... 20

Figure 2-20 MIKE 21 HD FM Model Validation at NOAA The Battery Tidal Station ..... 21

Figure 2-21 Comparison of Field Verified and Modeled Hurricane Sandy flood Extents (left) Field  
Verified Flood Map, (right) Flood Map Simulated by MIKE 21 HD FM Model ..... 22

Figure 2-22 MIKE 21 SW Model Mesh at the Project Site ..... 24

Figure 2-23 MIKE 3 Wave FM Model Horizontal Domain ..... 25

Figure 2-24 Overview of the MIKE 3 Wave FM Model Horizontal Mesh ..... 25

Figure 2-25 A closer view of the MIKE 3 Wave FM Model Horizontal Mesh near the Proposed  
Flood Resistant Alignment ..... 26

Figure 3-1 100-Year Storm Flood Maximum Stillwater Level for Project Area, without SLR, without  
project. .... 29

Figure 3-2 100-Year Storm Flood Maximum Stillwater Level for Project Area, with 2050s SLR,  
without project. .... 30

Figure 4-1 Proposed Flood Resistant Alignments. Solid red lines represent vertical walls or barriers.  
The dashed red line is the location of a floodwall that is that is covered by a sloped fill. .... 31

Figure 4-2 100-Year Coastal Stillwater Elevation Map (without SLR) with the Proposed Flood

---

Resistant Alignment (yellow) .....	32
Figure 4-3 100-Year Coastal Stillwater Elevation Map (with SLR) with the Proposed Flood Resistant Alignment (Scenario with no floodwall proposed for the WBPC Project Implemented) .....	33
Figure 4-4 Screenshot of the MIKE 21 SW Model Simulated Wave Field under 100-year Storm (no SLR) with the Proposed Flood Resistant Alignment, Wind Direction from 220 degree to North .....	34
Figure 4-5 Screenshot of the MIKE 21 SW Model Simulated Wave Field under 100-year Storm and 2050s SLR with the Proposed Flood Resistant Alignment, Wind Direction from 220 degree to North .....	35
Figure 4-6 MIKE 3 Wave Model Simulated 100-year Wave Condition under 100-year Storm Surge Peak and 2050s SLR with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side).....	36
Figure 4-7 MIKE 3 Wave Model Simulated Maximum Water Surface Elevation (Wave Crest Elevation) under 100-year Storm Surge Peak, 2050s SLR, and 100-year Wave Condition with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side).....	37
Figure 4-8 3D Snapshot of MIKE 3 Wave Model simulated 100-year Wave Field under 100-year Storm Surge Peak and 2050s SLR with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side).....	38
Figure 4-9 Sketch of Zone and Section Locations along the Proposed Flood Resistant Alignment .....	39

This Page has been Intentionally Left Blank.

---

## ACRONYMS

2D	Two-Dimension
ADCIRC	Advanced Circulation Model
CFL	Courant-Friedrichs-Lewy number
cfs	Cubic feet per second
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
FM	Flexible Mesh
ft	U.S. Feet
HD	Hydrodynamic
LIDAR	Light Detection and Ranging
LGA	La Guardia Airport
NAVD88	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
NLCD	National Land Cover Database
NOAA	National Ocean and Atmospheric Agency
NPCC	New York City Panel on Climate Change
RAMPP	Risk Assessment, Mapping, and Planning Partners
SLR	Sea Level Rise
SW	Spectral Wave
SWEL	Stillwater Elevation
SWL	Stillwater Level
TWL	Total Water Level
USACE	U.S. Army Corps of Engineers

---

WBPC	West Battery Park City
WSE	Water Surface Elevation

## **DEFINITIONS UNITS**

1 meter = 3.28084 feet

1 foot = 12 inches

## 1.0 INTRODUCTION

The Battery Park City Authority has contracted AECOM to provide engineering design services in support of the South Battery Park City (SBPC) Resiliency Project (the “Project”).

### 1.1 Project Area

The study area of the SBPC project includes a continuous flood barrier starting from the Museum of Jewish Heritage, through Wagner Park, across Pier A Plaza, and ending along the northern border of Historic Battery Park, as shown in Figure 1-1. This area represents one of the Battery Park City’s (and Lower Manhattan’s) vulnerable points to storm surge inundation and flooding.



Figure 1-1 Project Study Area Map

## 1.2 Objectives and Scope of Work

As part of the scope of work of the SBPC project, one of the primary objectives is to develop a coastal model system to assess the project area's vulnerability to flooding for existing conditions (with no flood protection implemented) and for the proposed flood resistant alignment, with and without Sea Level Rise (SLR) considered.

## 2.0 DEVELOPMENT OF COASTAL MODEL SYSTEM

Numerical mathematical models are commonly used in engineering practice, as they provide a convenient and reliable method for comparing project alternatives to existing conditions (baseline) under different combinations of coastal storm surges, waves, tides, and sea levels. For this Project, a suite of coastal models were applied and consisted of a regional-scale storm surge model ADCIRC, local-scale storm surge and wave models MIKE 21 Hydrodynamic FM Model, MIKE 21 Spectral Wave FM Model, and MIKE 3 Wave Model, and the EurOtop equations for computation of wave runup and overtopping. Ultimately the requirements for design or certification will depend on the calculated wave runup elevations, overtopping discharge rates and volumes, and wave forces along the project structure alignment. The final assessment of wave runup and overtopping was made using the EurOtop equations, with inputs coming from the MIKE 21 wave model results and from the most recent FEMA FIS study (FEMA, 2013) in the area.

### 2.1 Regional Coastal Storm Surge Model ADCIRC

For this Project, AECOM applied the two-dimensional ADCIRC coastal storm surge model developed as part of FEMA's New York/New Jersey storm surge study (RAMPP, Region II Storm Surge Project – Model Calibration and Validation, 2014) to provide regional boundary conditions for the MIKE 21 Hydrodynamic FM Model that was subsequently used to simulate the storm surge events in the SBPC Project's urban environment. The ADCIRC model domain extends from 97.85° to 60.04° W and from 7.90° to 45.83° N, encompassing the Western Atlantic, the Gulf of Mexico, and the Caribbean Sea.

ADCIRC is a system of computer programs for solving time-dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. One of ADCIRC's primary applications is the prediction of storm surge and flooding under extreme storm events. Storm surge is a rise in sea water level caused by extreme wind and pressure forces acting on the water surface. Water heights associated with storm surge are superimposed on water levels generated by tidal forcing. Past research and model experiences illustrate that the numerical model domain size has considerable effects on the accuracy of storm surge predictions; therefore, ADCIRC model domains often extend far beyond the local study area and out into the deep ocean. The ADCIRC model grid and domain are shown in Figure 2-1.

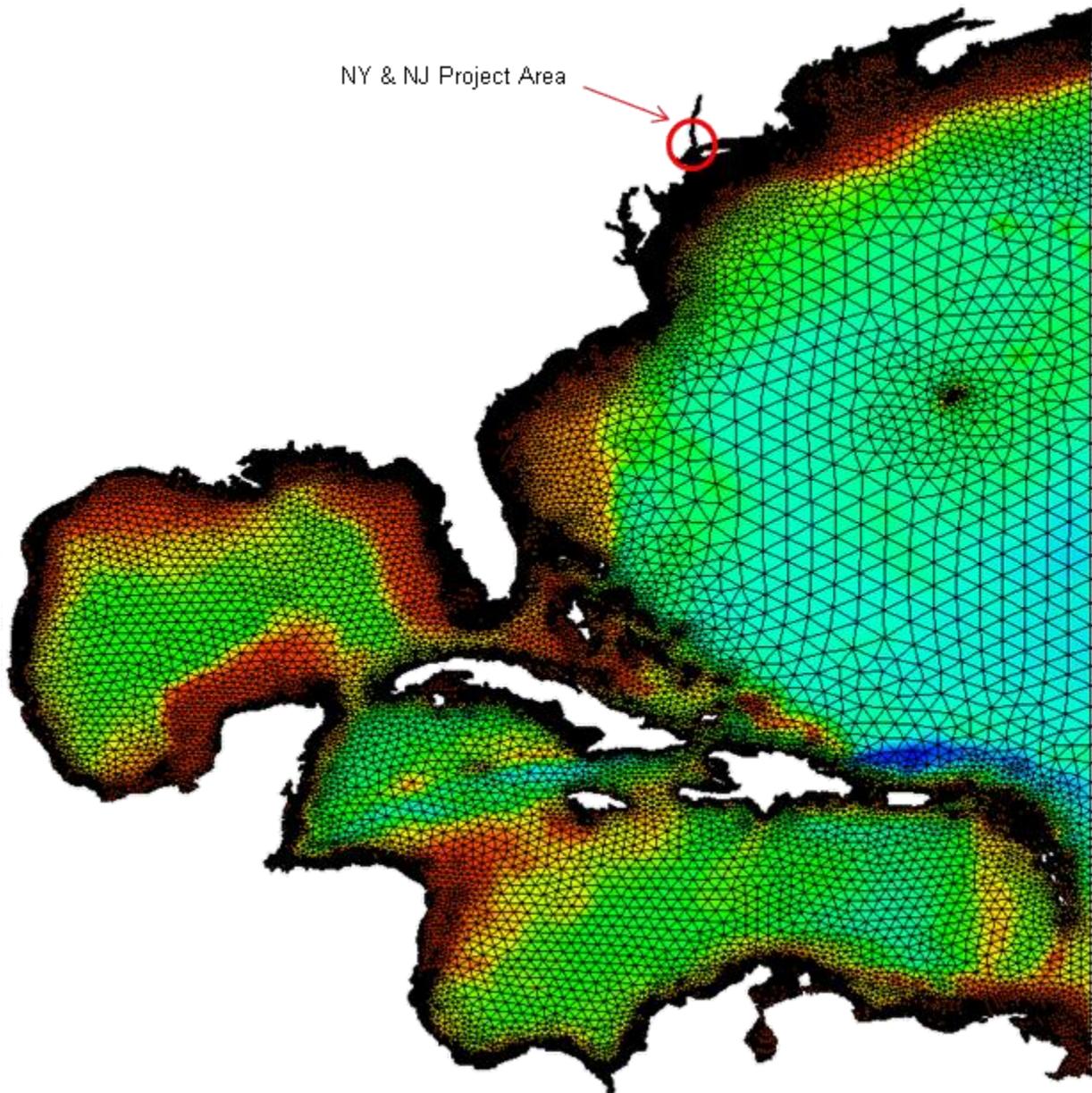


Figure 2-1 Numerical Grid and Model Domain of ADCIRC Model

## 2.2 MIKE 21 Hydrodynamic FM Model

The MIKE 21 hydrodynamic (HD) flexible mesh (FM) Model is a FEMA-accepted hydrodynamic model for conducting flood assessments. The flexible mesh approach allows for variations in the model resolution within the model domain. Consequently, MIKE 21 HD FM Model is especially suitable for the urban environment. The MIKE 21 HD FM Model is a depth-integrated 2D model applied for the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas, and seas. It simulates water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal regions. Capabilities of the MIKE 21 HD FM Model include:

- Bottom shear stress
- Wind shear stress
- Barometric pressure gradients
- Coriolis force
- Momentum dispersion
- Sources and sinks
- Rainfall and evaporation
- Flooding and drying
- Wave radiation stresses
- Direct dynamic coupling to the MIKE 21 Spectral Wave model

### 2.2.1 Topography and bathymetry

Topographic and bathymetric data are critical to the development of any hydrodynamic model. For this project, efforts were made to employ recent terrain data available, which include:

- Digital Elevation Model (DEM, both topography, and bathymetry) derived from post-Sandy LiDAR collected in November 2012 by the USACE Joint Airborne LiDAR Bathymetry Technical Centre of Expertise (JALBTCX).
- The Post-Sandy Digital Elevation Model (DEM, both topography, and bathymetry) from NOAA, April 2016.

To supplement DEM data, AECOM conducted a topographic and bathymetric survey to obtain elevations of existing waterfront structures, shoreline features, and bathymetry from the pier head to the shoreline. The extents of the waterfront topography and bathymetry are shown in Figure 2-2.

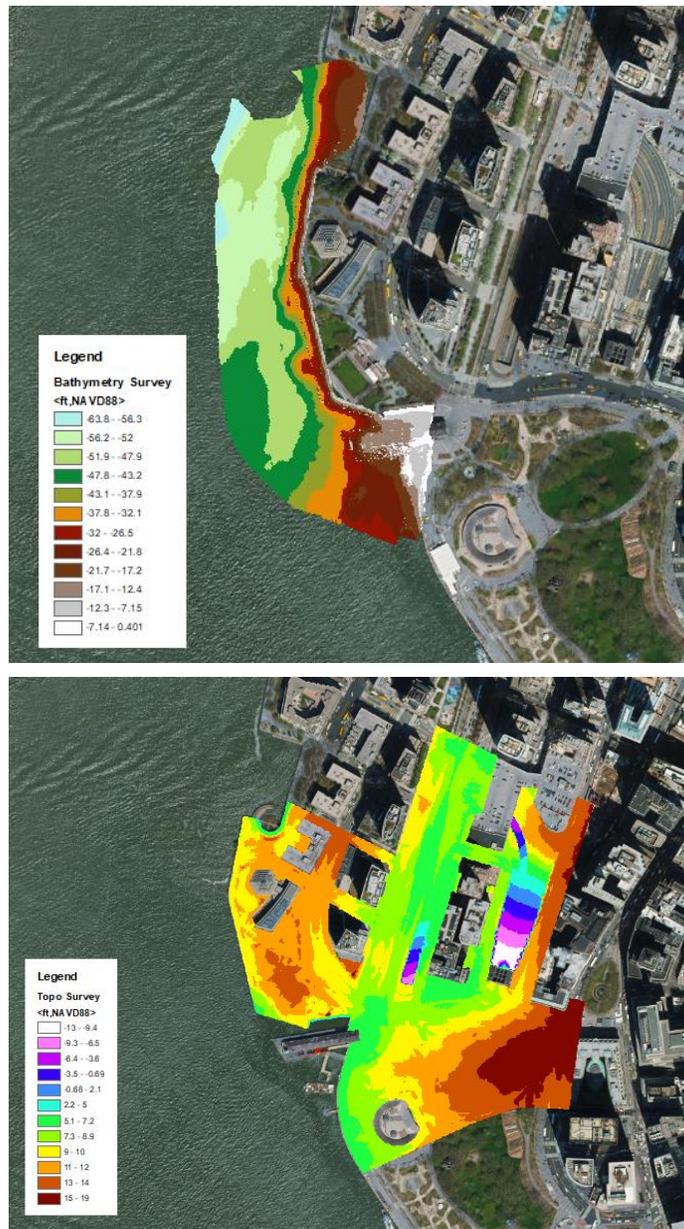


Figure 2-2 Extent of Topography and Bathymetry Surveys for Bathymetry Survey (top) and Topography Survey (bottom).

## 2.2.2 Model Domain and Mesh

The overview of the MIKE 21 HD FM model domain and mesh are shown in Figure 2-3 and Figure 2-4. The Horizontal Coordinate System of the 2D figures in this report is UTM-18, NAD83, US Feet. Figure 2-5 shows the refined mesh at the project site.

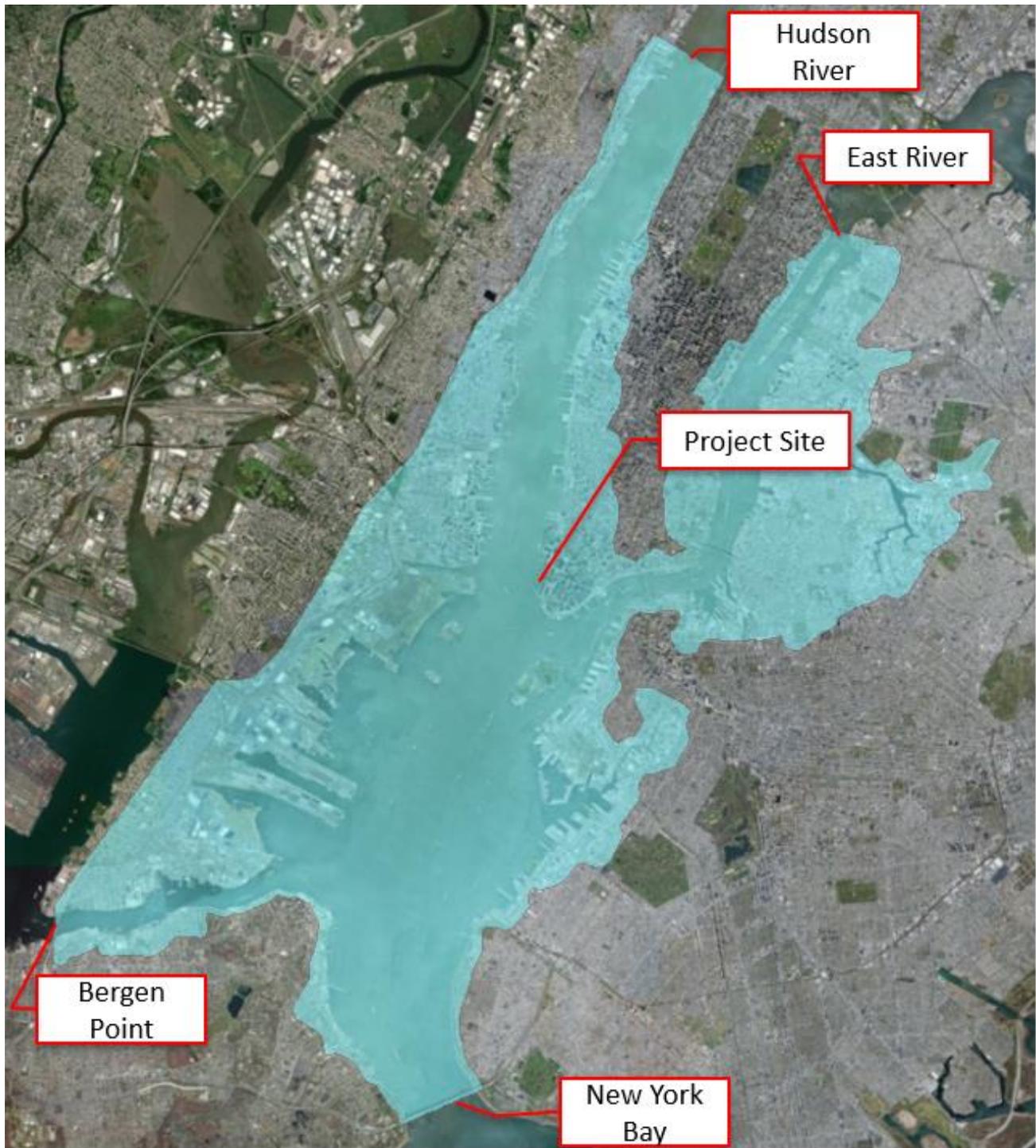


Figure 2-3 Overview of MIKE 21 HD FM Model Domain and Boundary Locations

[ft US]

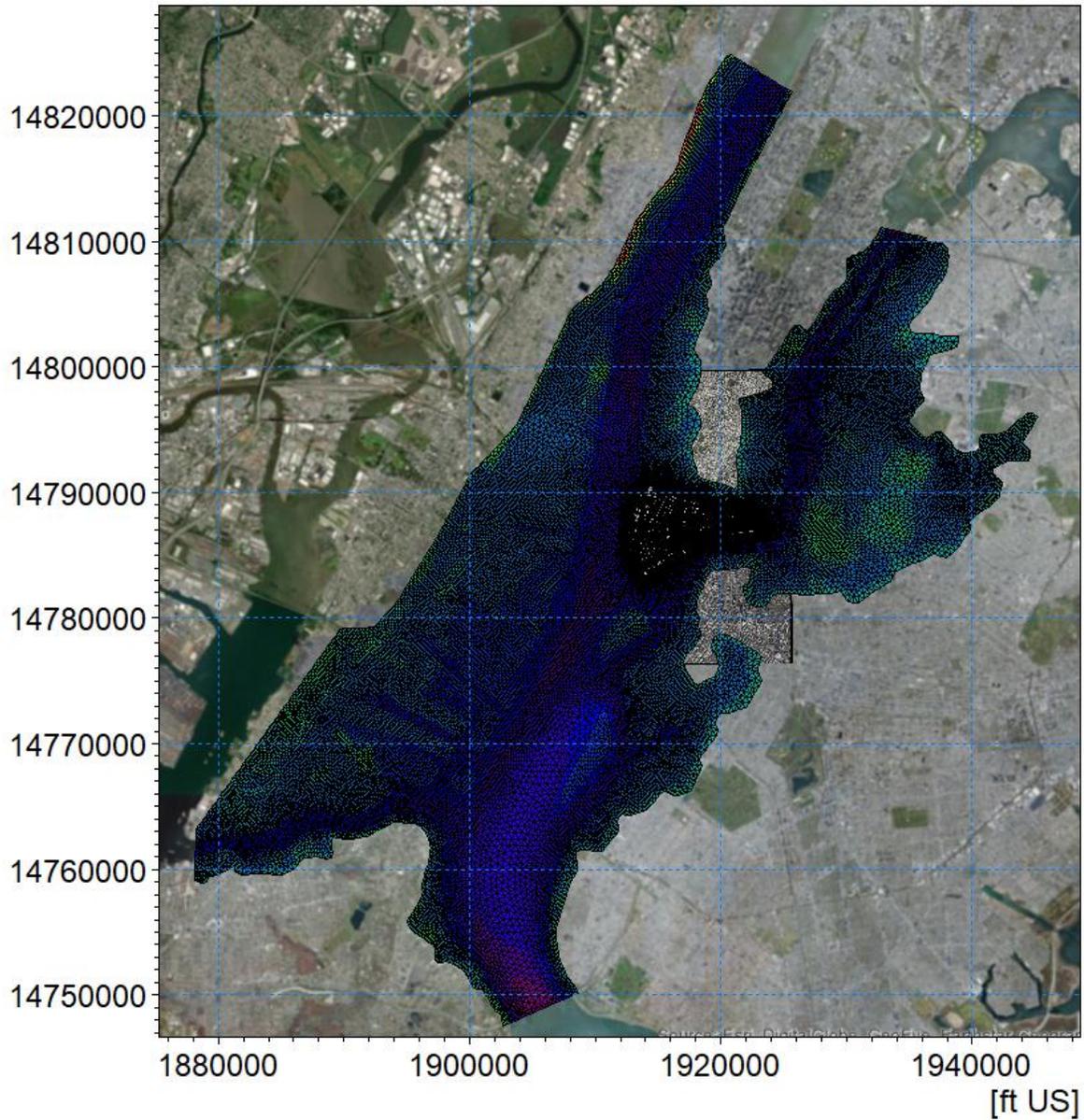


Figure 2-4 Overview of MIKE 21 Hydrodynamic Model Mesh

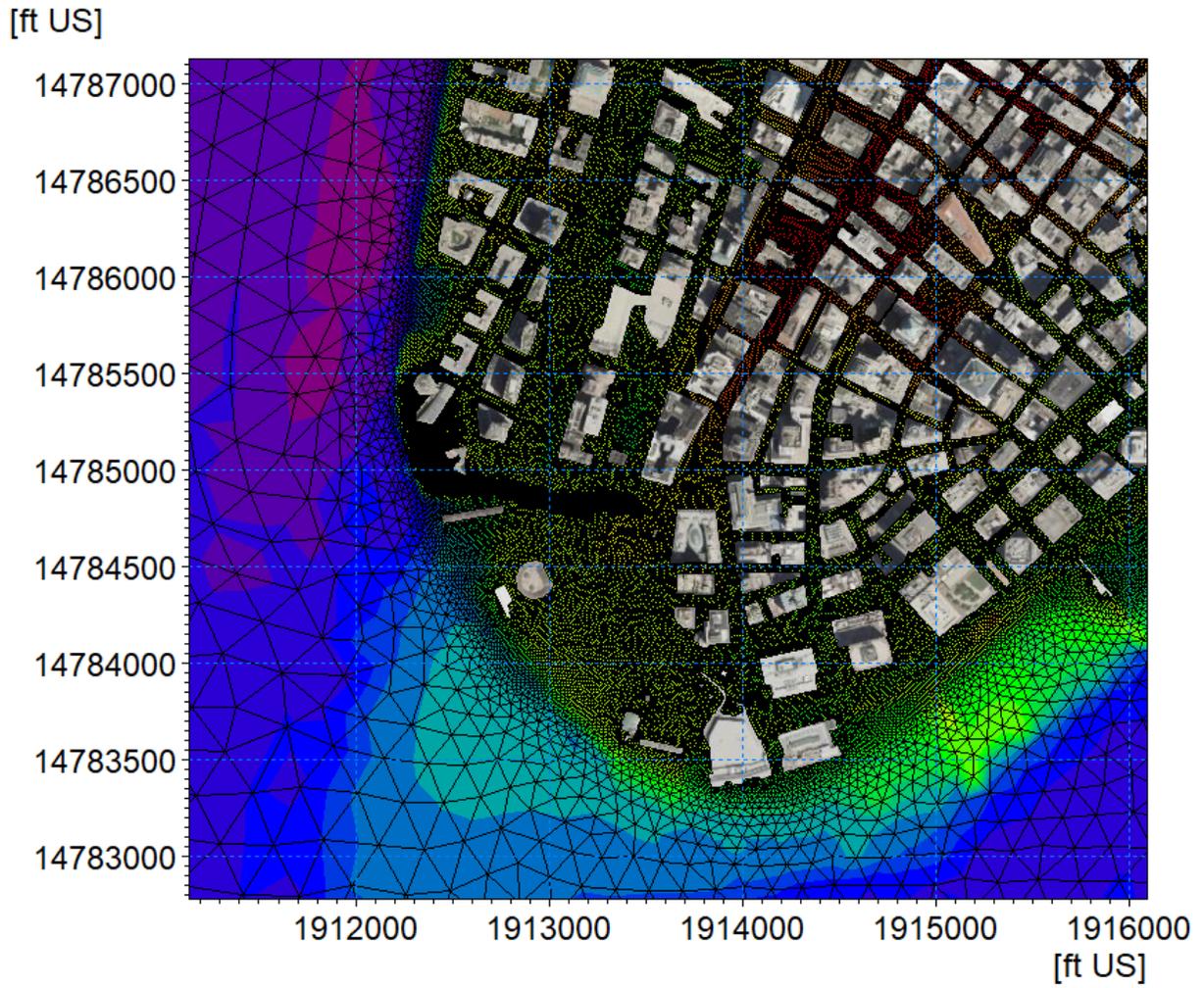


Figure 2-5 MIKE 21 Hydrodynamic Model: Refined Mesh at Project Site

### 2.2.3 Model Setup

The MIKE 21 HD FM model setup parameters are summarized in Table 2-1.

**Table 2-1 Summary of MIKE 21 HD FM Model Setup Parameters**

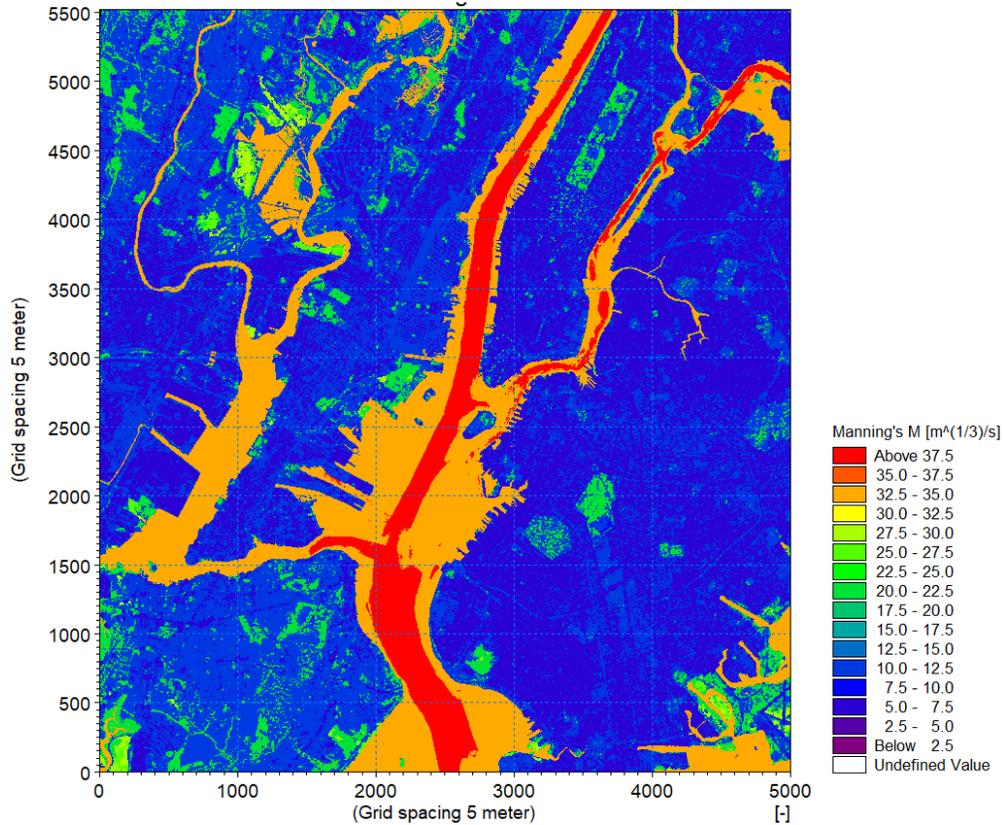
Parameter	Value / Note
The study area for mesh	62 square miles
Model mesh	about 0.3 million elements; average element length in the project area is on the order of 16 ft. Mesh element size in the model domain varies from 1.5 ft to 350 ft. Element size indicates the approximate length of a triangular element side.
Model time step	Overall time step interval: 30-second (frequency of output). Time step for hydrodynamic model: dynamic and each determined to satisfy stability criteria (Courant-Friedrichs-Lewy condition < 0.8).
Boundary conditions	Flather condition: (time series of surface water elevations and velocities extracted from the ADCIRC model applied along each model open boundary)
Flood and dry	Included. Drying depth: 0.0164 ft Flooding depth: 0.033 ft Wetting depth: 0.33 ft
Bed roughness	Manning's M (1/Manning's n), varying from 7 to 50 in the domain
Horizontal eddy viscosity	Smagorinsky coefficient: 0.28 as initial
External forcing	Domain varying time series of wind and pressure forcing (source: Oceanweather Inc.) included

During the model setup, the bed roughness map was created using the Manning's n-values categorically assigned to the land use data downloaded from the National Land Cover Database (NLCD) website. The NLCD's Land Use GIS data consists of 16 different land use classifications to use in the coastal model. The Manning's n-values corresponding to land use classification were assigned based on the literature and on published Manning's n-values from a coastal storm surge study conducted for FEMA by Risk Assessment, Mapping, and Planning Partners (RAMPP, Region II Storm Surge Project – Spatially Varying Nodal Attribute Parameters, 2014). Table 2-2 below summarizes the land use classifications and Manning's n-values used in the model setup.

**Table 2-2 Land Use Classifications and Manning's Values for MIKE 21 Model**

Land Use Name	Manning's n-Value for Model Setup	Manning's M-Value for Model Setup
Open Water	0.03	33.3
Open Water (deep)	0.02	50
Developed, Open Space	0.05	20
Developed, Low Intensity	0.10	10
Developed, Medium Intensity	0.10	10
Developed, High Intensity	0.15	6.7
Shrub/Scrub	0.05	20
Herbaceous	0.035	28.6
Wetlands	0.05	20

Figure 2-6 shows the Manning's M-values for the MIKE 21 model. Manning's M-values are the reciprocal of the Manning's n-values (i.e.,  $M = 1/n$ ).



**Figure 2-6 Manning's M for MIKE 21 Hydrodynamic Model**

## 2.3 ADCIRC and MIKE 21 HD FM Model Calibration and Validation

The coastal model system requires calibration and validation before the actual project runs could be conducted. The model calibration for the ADCIRC and MIKE 21 HD FM models was based on the comparison of model predicted time series of (1) tidal water levels during a 15-day tide which includes the spring and neap tides and (2) water levels during the 1984 Nor'easter (03/28/1984 ~ 03/29/1984) with measured water levels at NOAA tidal stations (see Figure 2-7). NOAA's The Battery, Bergen Point, and Sandy Hook stations were used for ADCIRC comparisons. NOAA's The Battery station was used for MIKE 21 HD Model calibration. The ADCIRC model was validated based on the comparison of measured and modeled time series of water level at NOAA stations during Hurricane Sandy. The MIKE 21 HD FM Model validation involved a comparison of the model's predicted extent of flooding during Hurricane Sandy compared to a field verified flood map.



**Figure 2-7 Location of the NOAA tidal stations at The Battery, Bergen Point, and Sandy Hook**

### 2.3.1 Model Calibration

For the calibration against tide, the comparisons of time series of ADCIRC model-predicted versus NOAA-predicted tide water levels at NOAA tidal stations at The Battery, Bergen Point, and Sandy Hook are shown in Figure 2-8, Figure 2-9 and Figure 2-10. The statistics of the comparisons are listed in Table

2-3. Figures 2-8, Figure 2-9, Figure 2-10, and Table 2-3 demonstrate the close agreement between the ADCIRC model predicted tide water levels and the observed tide water levels.

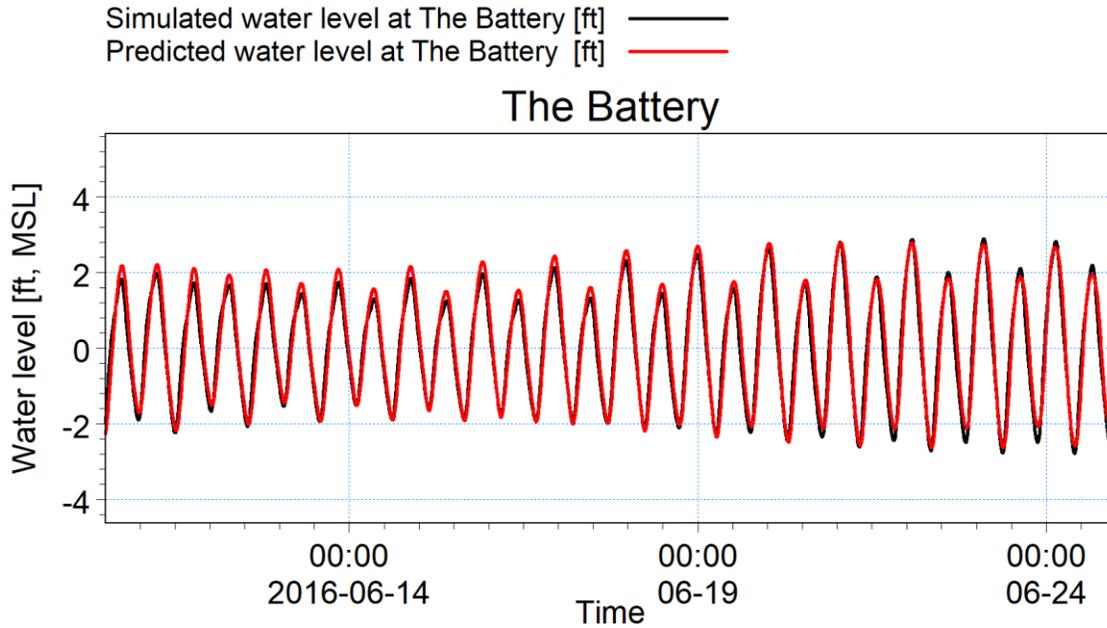


Figure 2-8 ADCIRC Model: Calibration with Tide at NOAA The Battery Tidal Station

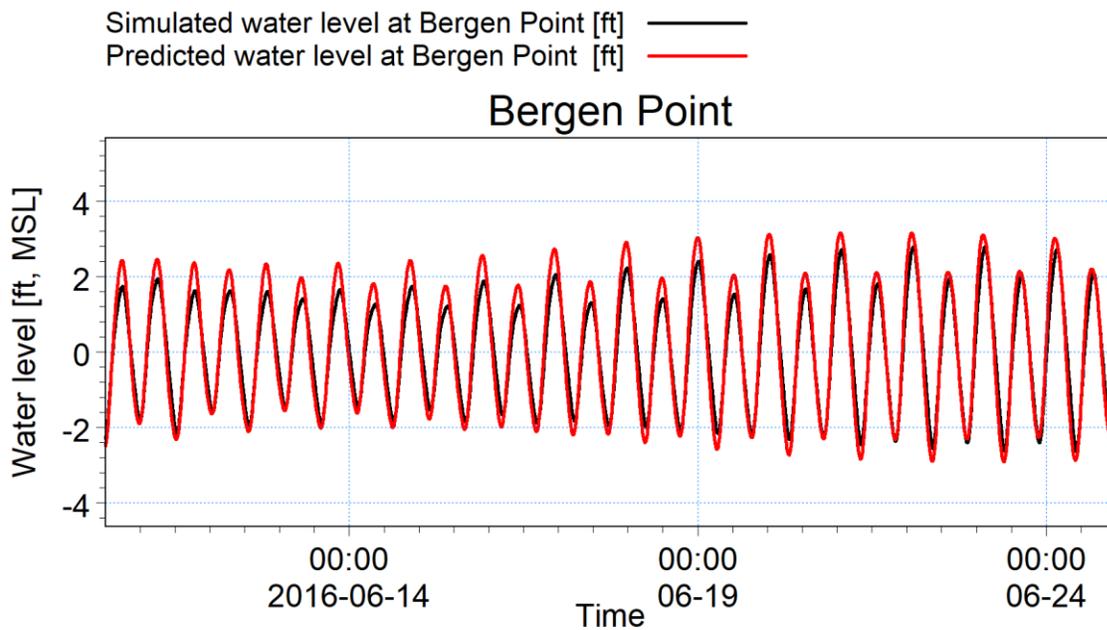


Figure 2-9 ADCIRC Model: Calibration with Tide at NOAA Bergen Point Tidal Station

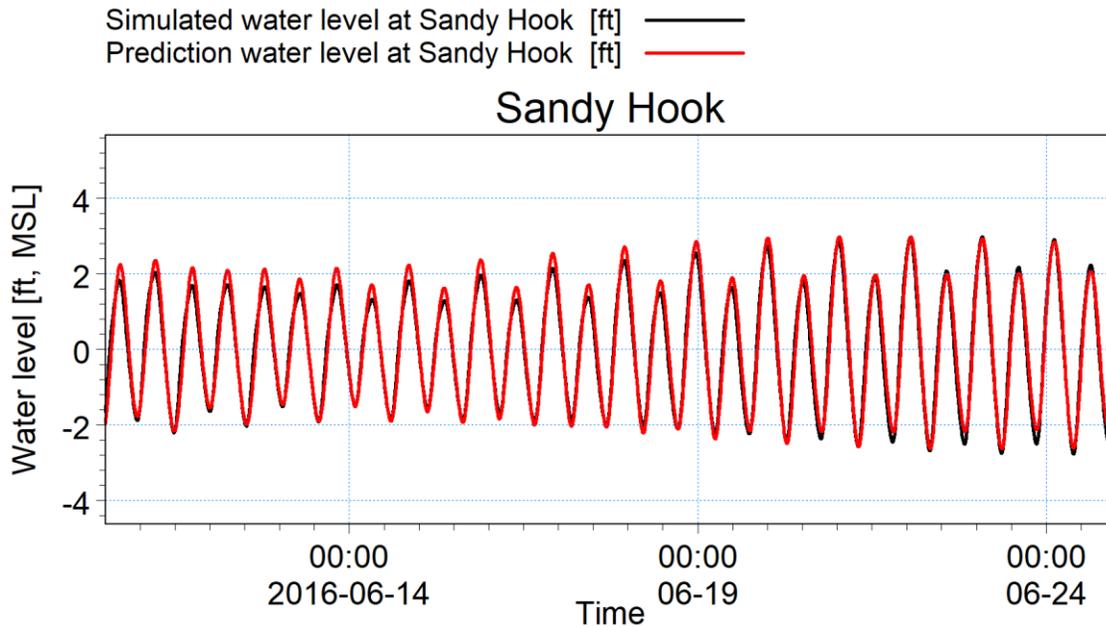


Figure 2-10 ADCIRC Model: Calibration with Tide at NOAA Sandy Hook Tidal Station

Table 2-3 Summary statistics of the ADCIRC Model Calibration with Tide

	The Battery	Bergen Point	Sandy Hook
Mean Absolute Error [feet]	0.26	0.34	0.20
Root Mean Square Error [feet]	0.31	0.41	0.25
R <sup>2</sup>	0.96	0.97	0.98

Besides the normal tide, the ADCIRC model was also calibrated against the 1984 Nor'easter (03/28/1984 ~ 03/29/1984). Figure 2-11, Figure 2-12 and Figure 2-13 show the comparisons of model simulated and measured water levels at The Battery, Bergen Point, and Sandy Hook tidal stations. The statistics of the comparisons are listed in Table 2-4.

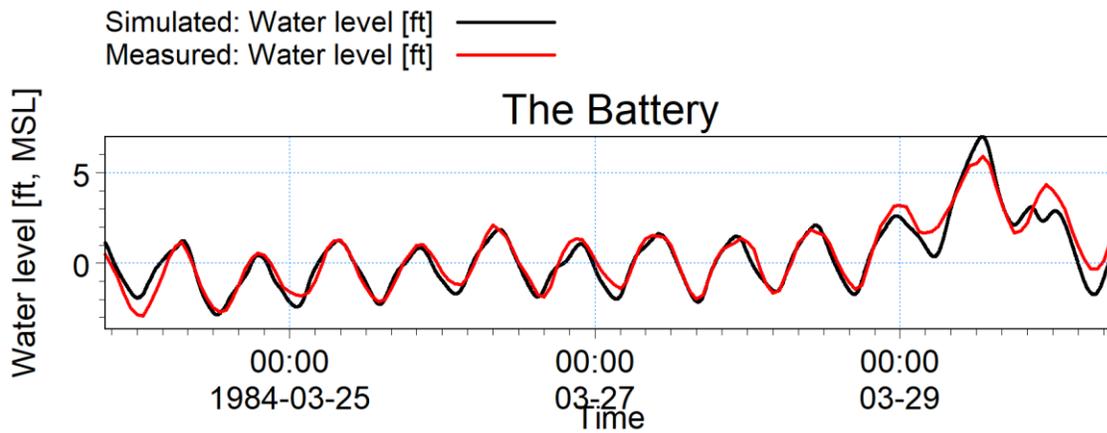


Figure 2-11 ADCIRC Model: Calibration with 1984 Nor'easter at NOAA The Battery Tidal Station

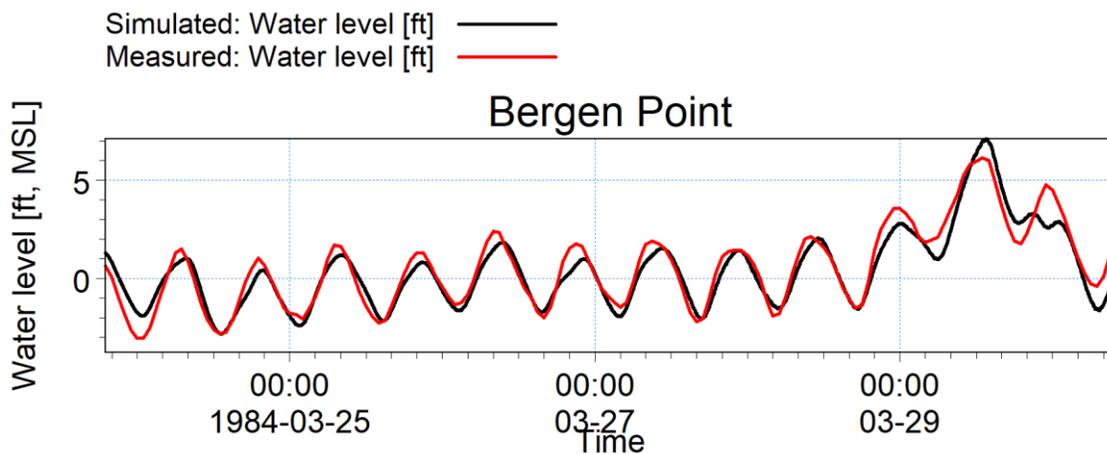


Figure 2-12 ADCIRC Model: Calibration with 1984 Nor'easter at NOAA Bergen Point Tidal Station

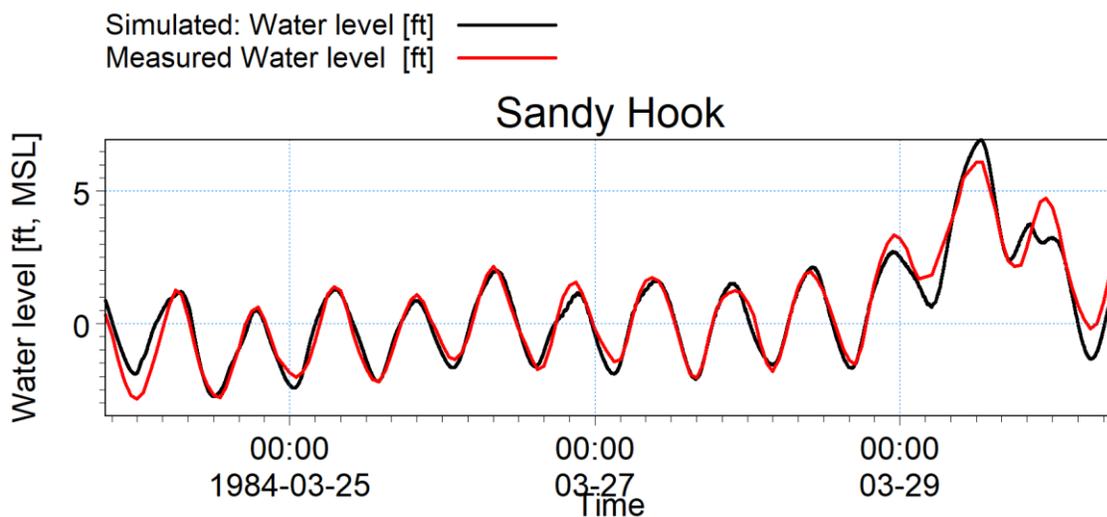


Figure 2-13 ADCIRC Model: Calibration with 1984 Nor'easter at NOAA Sandy Hook Tidal Station

**Table 2-4 Summary statistics of the ADCIRC Model Calibration with 1984 Nor'easter**

	<b>The Battery</b>	<b>Bergen Point</b>	<b>Sandy Hook</b>
Mean Absolute Error [feet]	0.43	0.53	0.38
Root Mean Square Error [feet]	0.57	0.68	0.51
R <sup>2</sup>	0.91	0.89	0.93
Peak Difference, Model minus Measured (feet)	1.08	0.95	0.84

It should be noted that although the peak water levels at the tidal stations during the 1984 Nor'easter are overpredicted, the time series of the simulated water levels are identical to the modeled water levels reported in FEMA's calibration and validation of the ADCIRC model (RAMPP, Region II Storm Surge Project – Model Calibration and Validation, 2014). Generally, given the close comparisons between the study modeling and the RAMPP modeling for FEMA, and that FEMA has used these results previously where rigorous calibration and validation was performed, either set of data would be suitable for application to this study without further adjustment.

, The same 15-day tidal cycle event and the 1984 Nor'easter against which the ADCIRC model was calibrated were simulated was used to calibrate the local MIKE 21 HD FM Model. The simulated time series of water level at NOAA's Battery tidal station, which is not far away from the Project site (see Figure 2-14), was compared against the measured data. Figure 2-15 shows the comparison of simulated and measured water levels during the tidal cycle. The statistics of the comparison are shown in Table 2-5. Figure 2-15 and Table 2-5 demonstrate the close agreement between the MIKE 21 simulated tidal water levels and the observed tidal water levels at The Battery station.



Figure 2-14 Location of NOAA's Battery Tide Station

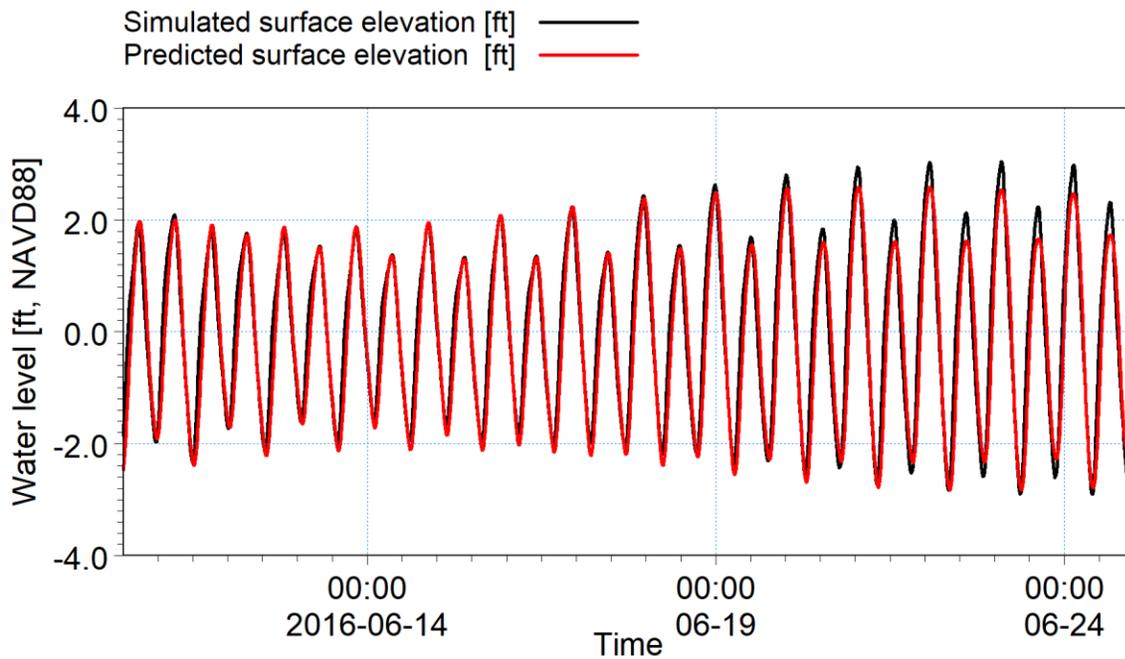


Figure 2-15 MIKE 21 HD FM Model: Calibration with Tide at NOAA’s Battery Station

Table 2-5 Summary statistics of the MIKE 21 HD FM Model Calibration with Tide

	The Battery
Mean Absolute Error [feet]	0.34
Root Mean Square Error [feet]	0.43
R <sup>2</sup>	0.93

The figure and statistics of the comparison of MIKE 21 HD FM model simulated and the measured water levels during the 1984 Nor’easter are shown in Figure 2-16 and Table 2-6, respectively. Consistent with the ADCIRC simulation results and the modeled water levels reported in FEMA’s calibration and validation of the ADCIRC model (RAMPP, Region II Storm Surge Project – Model Calibration and Validation, 2014), the peak water level is overpredicted. But an R<sup>2</sup> of 0.92 still demonstrates a good agreement and no adjustment to the MIKE 21 HD FM model was required.

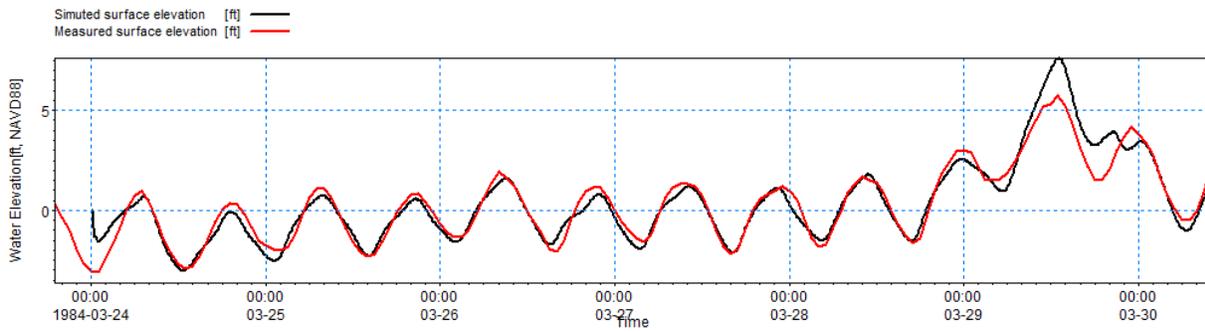


Figure 2-16 MIKE 21 HD FM Model: Calibration with 1984 Nor'easter at NOAA The Battery Station

Table 2-6 Summary statistics of the MIKE 21 HD FM Model Calibration with 1984 Nor'easter

	The Battery
Mean Absolute Error [feet]	0.47
Root Mean Square Error [feet]	0.61
R <sup>2</sup>	0.92
Peak Difference, Model minus Measured (feet)	1.66

### 2.3.2 Model Validation

Model validation involves the comparison of model-predicted storm surge with the observed storm surge during major storm events. Hurricane Sandy is one of the most destructive storms in the history of the NY/NJ region and is also the storm with the most recent field records of the flood extent. Consequently, it was chosen as the storm for model validation. For the validation of the ADCIRC model, the comparisons of time series of the model-predicted storm surge at NOAA Tidal Stations at The Battery, Bergen Point, and Sandy Hook are presented in Figure 2-17, Figure 2-18 and Figure 2-19, respectively.

Figure 2-17, Figure 2-18 and Figure 2-19 demonstrate the close agreement between the ADCIRC simulated and measured water levels during Hurricane Sandy at the tidal stations in the vicinity of the Project Area. The statistics of the comparisons are listed in Table 2-7.

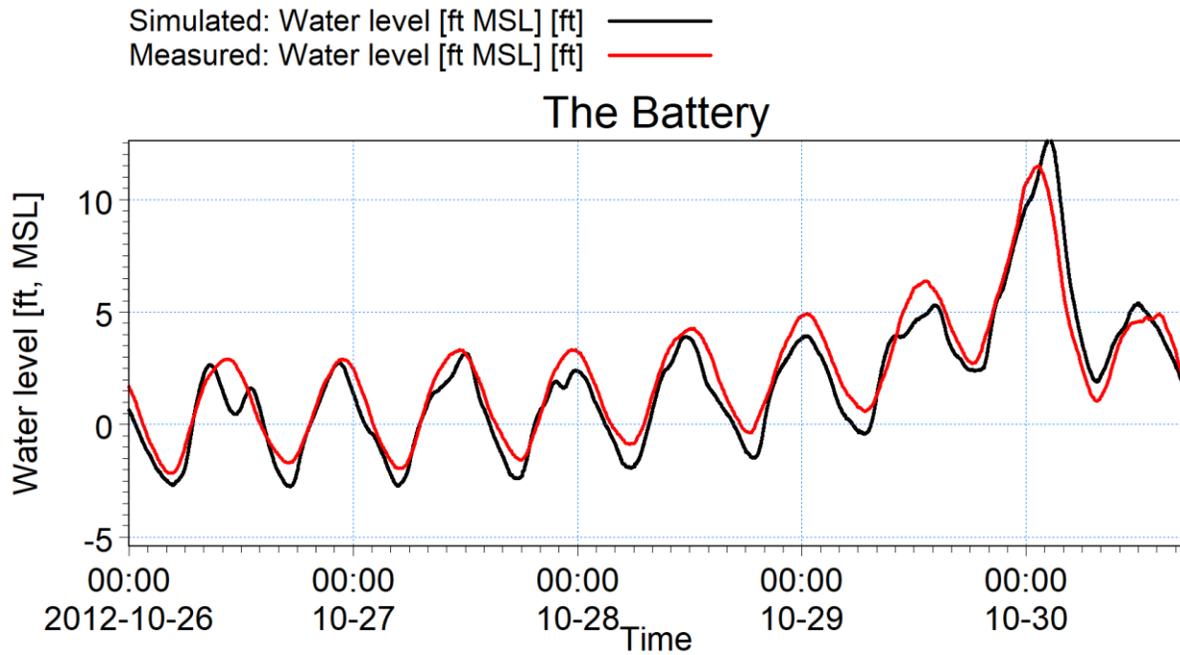


Figure 2-17 ADCIRC Model Validation at NOAA The Battery Tidal Station

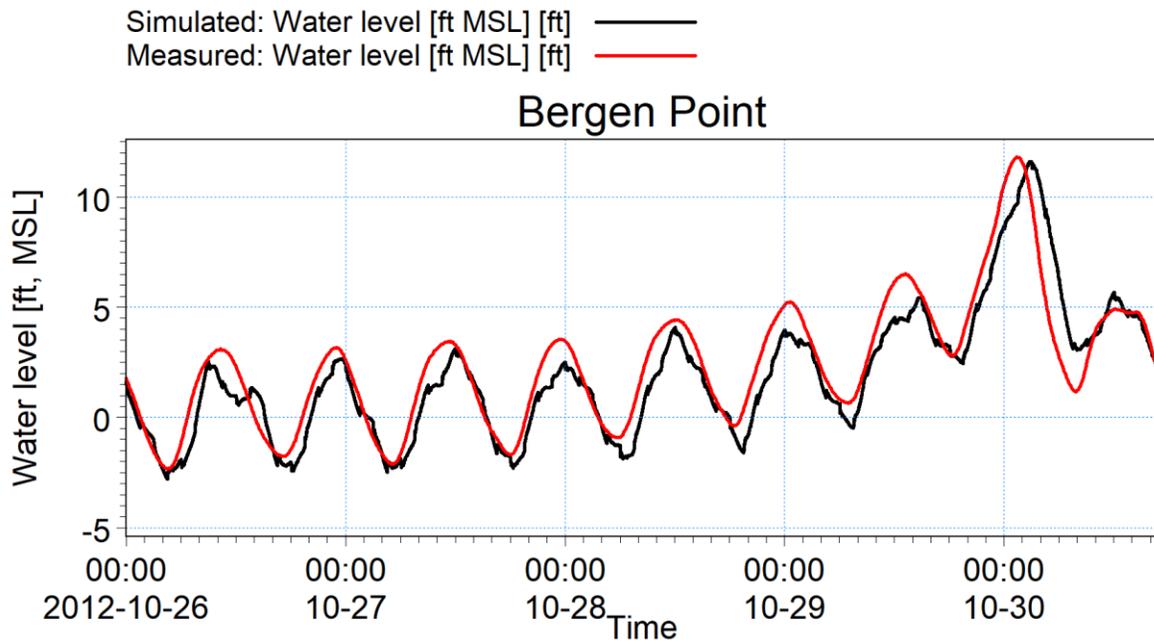


Figure 2-18 ADCIRC Model Validation at NOAA Bergen Point Tidal Station

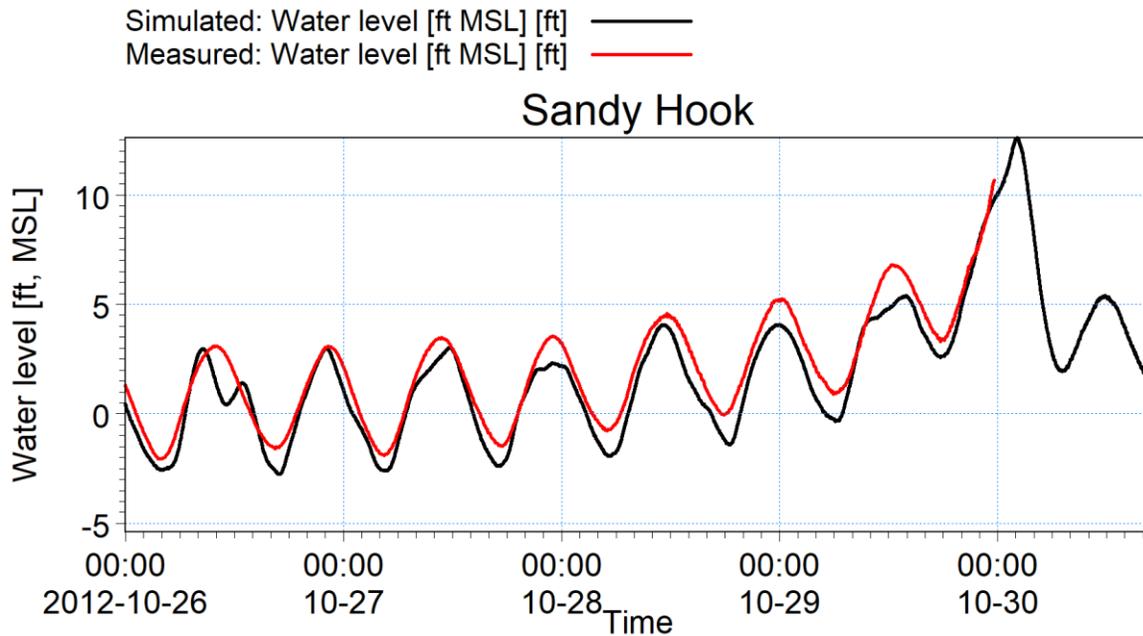


Figure 2-19 ADCIRC Model Validation at NOAA Sandy Hook Tidal Station

Table 2-7 Summary Statistics of the ADCIRC Model Validation for Hurricane Sandy

	The Battery	Bergen Point	Sandy Hook
Mean Absolute Error [feet]	0.72	0.78	0.73
Root Mean Square Error [feet]	0.95	1.08	0.98
R <sup>2</sup>	0.88	0.84	0.86
Peak Difference, Model minus Measured (feet)	1.11	-0.20	--

The local MIKE 21 HD FM Model was validated by comparing the simulated and measured water levels at NOAA The Battery tidal station, and the simulated and field verified flood extents during Hurricane Sandy. Figure 2-20 shows the comparison of time series of simulated and measured water levels at The Battery tidal station. The statistics of the comparison of time series are shown in Table 2-8. The comparison of the extents of flooding for Hurricane Sandy between the field records provided by FEMA Modeling Task Force and the MIKE 21 HD FM model result is shown in Figure 2-21. In general, the simulation and measurement agree closely with each other in terms of the water level at The Battery tidal station and the flood extents. The peak difference is similar over-prediction as observed with the ADCIRC model.

Overall, given the acceptable mean error and RMSE calculated between the model and measured water levels, the model is considered successfully validated for simulation of Hurricane Sandy and all model inputs have been finalized.

The MIKE 21 HD FM model was primarily used to assess preliminary design with regard to potential flood flow paths and to inform placement of flood control structures.

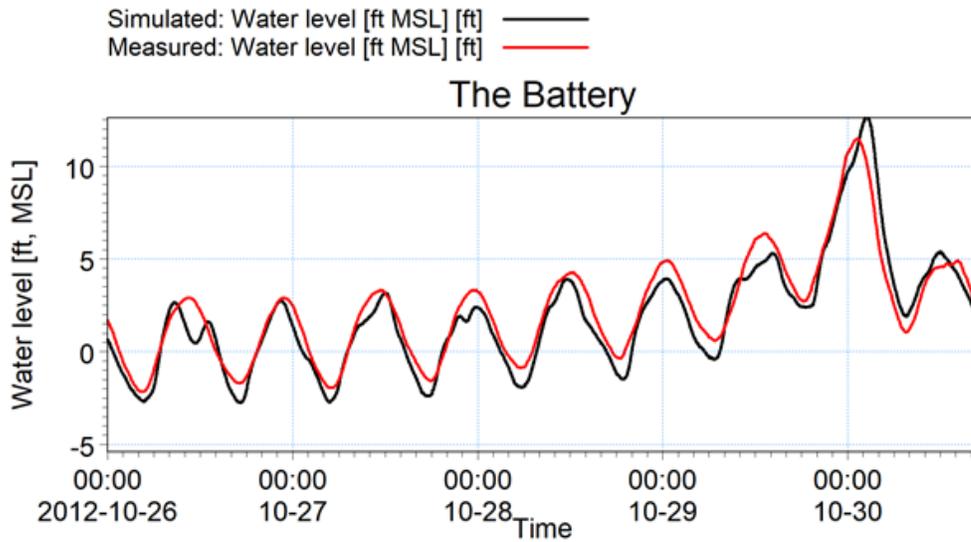


Figure 2-20 MIKE 21 HD FM Model Validation at NOAA The Battery Tidal Station

Table 2-8 Summary Statistics of the MIKE 21 HD FM Model Validation with Hurricane Sandy

	The Battery
Mean Absolute Error [feet]	0.86
Root Mean Square Error [feet]	1.02
R <sup>2</sup>	0.91
Peak Difference, Model minus Measured (feet)	1.66



## **2.4 Wave Models**

Given the location of the project site and its exposure to waves, the wave's effect on the design of flood countermeasures is significant. In order to reasonably simulate the wave field at the project site, the MIKE 21 Spectral Wave (SW) Model and the 3D MIKE 3 Wave Model were used. Results extracted from the MIKE 21 SW model boundary were then applied as boundary conditions into EurOtop equations to compute wave runoff and wave overtopping at discrete transect locations. MIKE 3 Wave was primarily used to inform preliminary design concepts.

### **2.4.1 MIKE 21 Spectral Wave Model**

As a phase-averaging model, the MIKE 21 SW wave model was developed to simulate the wave generation and transformation (such as wave shoaling, refraction, diffraction, wave-wave interaction, and breaking, etc) in the relatively larger model domain. This fully spectral model is able to solve the physical phenomena such as wave growth by action of wind, non-linear wave-wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to depth-induced wave breaking, refraction and shoaling due to depth variations, wave-current interaction, etc.

The quasi-static fully-spectral MIKE21 Spectral Wave model was applied to investigate the local wave conditions generated by wind in the range of 180 degrees to 270 degrees, relative to North, "coming from". The omnidirectional 100-year hourly wind speed of 25.3 m/s was applied, based on the analysis of LGA airport wind observations. This can be compared to local winds measured during Sandy of about 21 m/s. The results of the wave model in deeper water near the project site were output to provide the boundary condition for the MIKE 3 Wave Model.

The MIKE 21 SW model has the same mesh as the MIKE 21 HD FM model. Figure 2-22 shows the local MIKE21 SW model mesh. Existing building footprints were built into the mesh as islands.

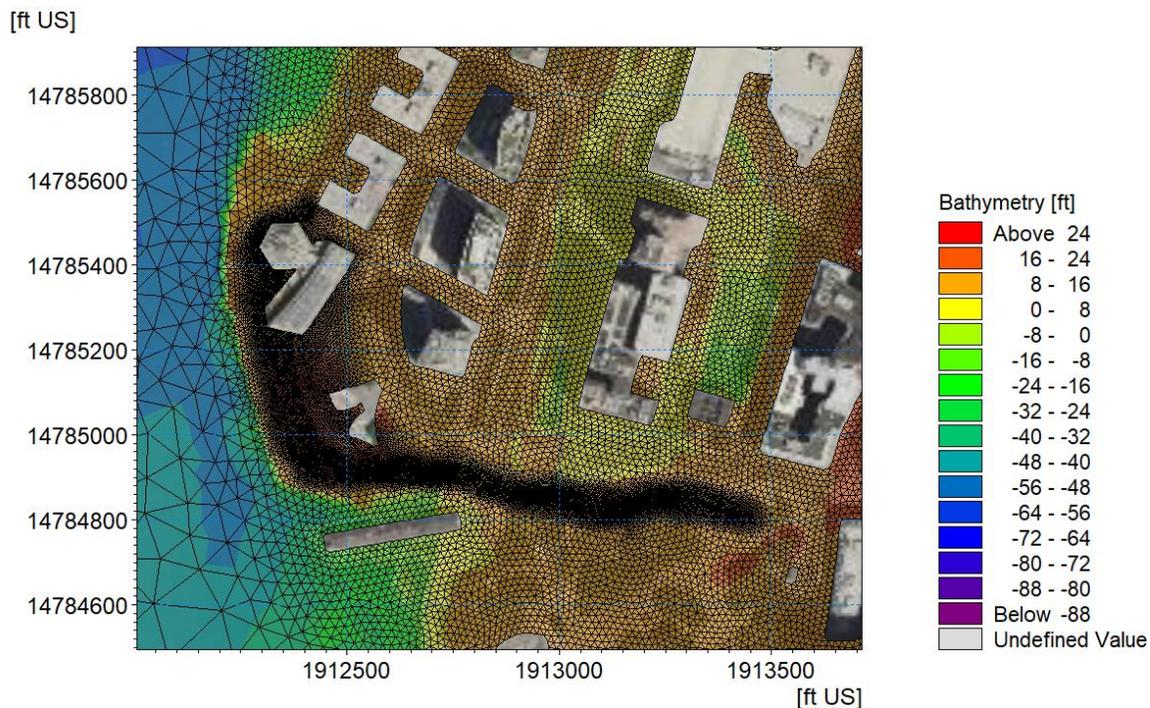


Figure 2-22 MIKE 21 SW Model Mesh at the Project Site

### 2.4.2 MIKE 3 Wave Model

The MIKE 3 Wave Model FM is a 3D phase-resolving wave model based on the numerical solution of the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations. The model consists of continuity and momentum equations and is closed by a turbulence closure scheme. A shock-capturing scheme (Riemann solver), which enables the stable simulation of flows involving shocks and discontinuities such as bores and hydraulic jumps which are common in the wave breaking process, is used to describe dissipation to processes such as wave breaking. The numerical techniques applied are based on an unstructured (flexible) mesh approach in the horizontal and utilizes a sigma coordinate transformation approach in the vertical. The MIKE 3 Wave Model FM can simulate complicated wave processes such as wave breaking, wave run-up, and wave overtopping for coastal flooding projects.

The MIKE 3 wave model was used to simulate the wave conditions and overtopping at the Project site to inform the preliminary design phase of the study. The horizontal plan view of the MIKE 3 wave model domain is shown in Figure 2-23. The unstructured horizontal mesh consists of about 201,500 triangular elements with mesh size varying from 1.2 feet offshore to 0.3 foot near the proposed alignment. Figure 2-24 presents an overview of the horizontal mesh, while a closer view of the horizontal mesh near one of the proposed alignments can be found in Figure 2-25. Vertically a boundary fitting mesh was used, where an equidistant vertical discretization with 5 layers was applied. The total number of elements in the 3D unstructured mesh was about 1,000,000.



Figure 2-23 MIKE 3 Wave FM Model Horizontal Domain

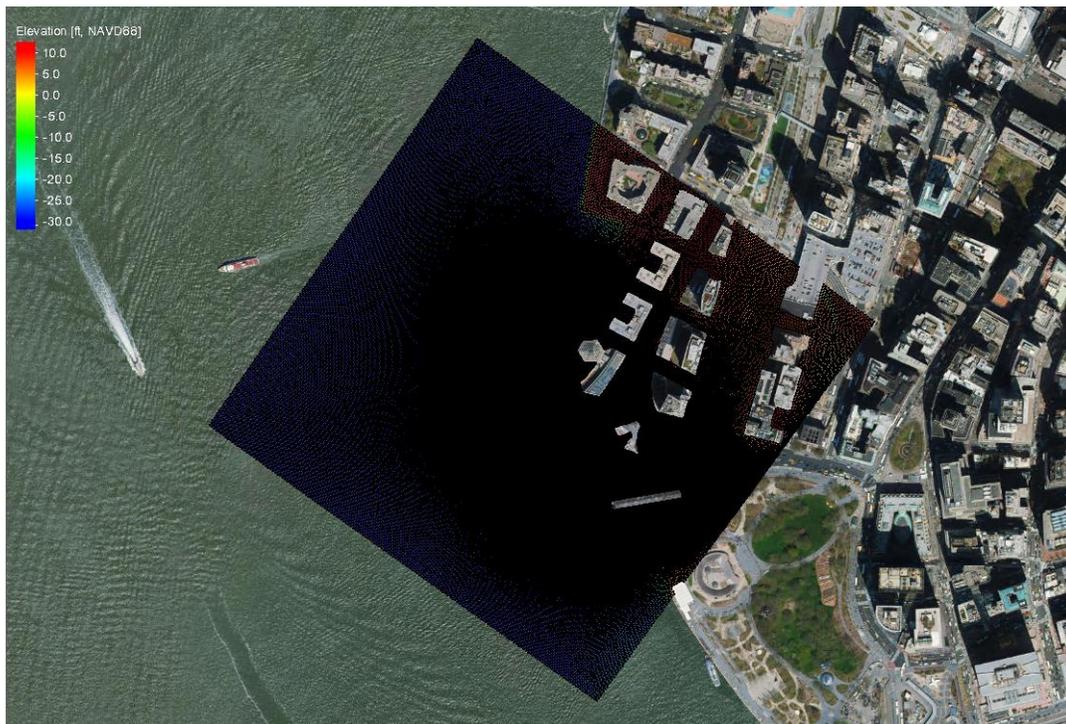
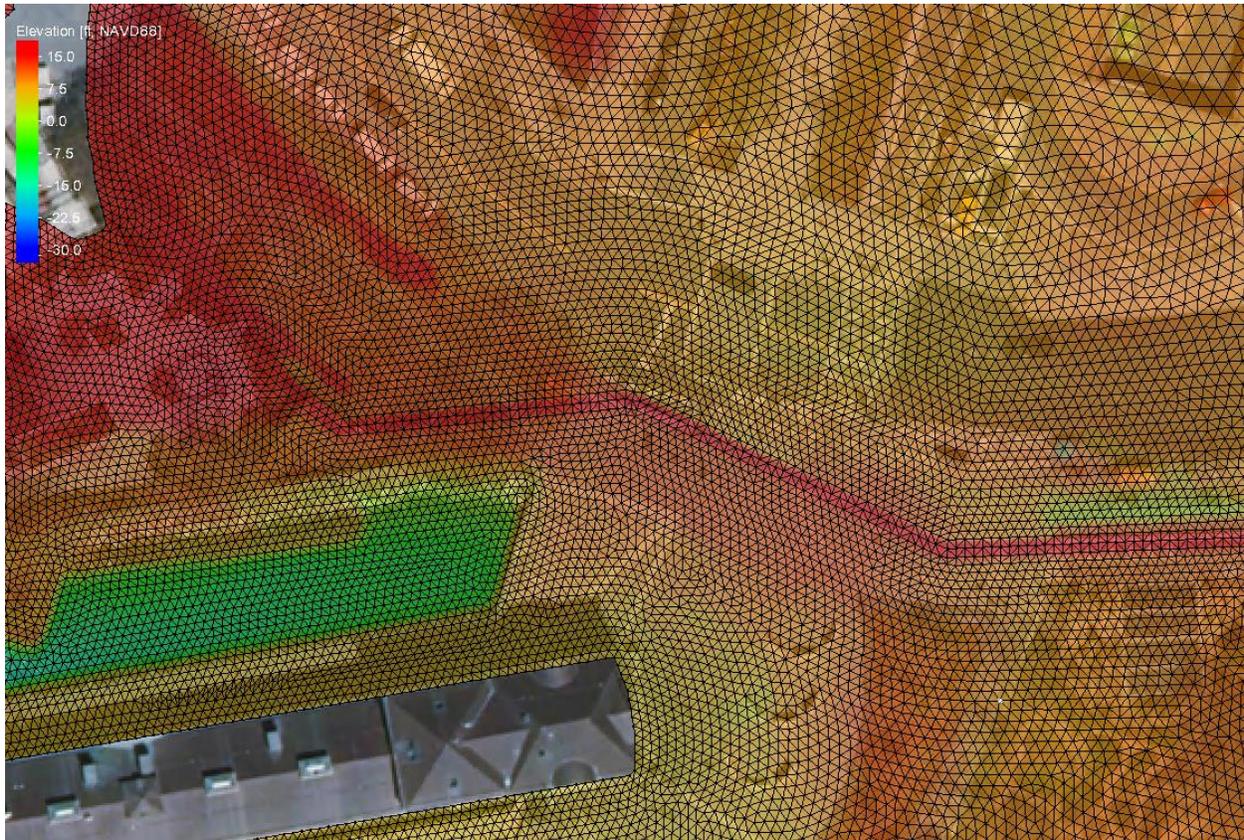


Figure 2-24 Overview of the MIKE 3 Wave FM Model Horizontal Mesh



**Figure 2-25 A closer view of the MIKE 3 Wave FM Model Horizontal Mesh near the Proposed Flood Resistant Alignment**

The incident waves conditions to be generated at the offshore boundary was extracted from the results of the MIKE 21 SW model simulation for the waves posing the biggest threat to the proposed flood resistant structure. Two 164 feet wide sponge layers are placed along the northwest and southeast boundaries to absorb the waves. The turbulence is modeled using an eddy viscosity concept.  $k - \epsilon$  model, a turbulence closure which has been widely used in the coastal wave models, is adopted for the present project. It is applied in both horizontal and vertical directions.

It should be noted that even though the MIKE 3 wave model does not include the local effect of winds on local wave generation, given the very short fetch lengths in the small domain, the additional wind-wave growth within the domain would be negligible compared to the incident waves.

## **3.0 COASTAL FLOOD ASSESSMENT FOR EXISTING CONDITION**

### **3.1 Identification of Coastal Storm**

The coastal storm for the design of the proposed flood alignment system is based on the 100-year return period (or 1% annual exceedance probability (AEP) probability event). A coastal storm event which generates a 100-year storm surge stillwater elevation (SWEL) was initially considered as the 100-year coastal storm event for the site. The local 100-year SWEL in the project area is about 11.3 ft NAVD88, based on the preliminary FEMA FIS Report (2013), and which also corresponds to the highest water level recorded at NOAA's "The Battery" tide station of 11.27 ft NAVD88 which occurred during Hurricane Sandy. One storm from the RAMPP study report for the FEMA preliminary FIS, NJb\_0003\_010, was identified for modeling the 100-year SWEL storm event. From the model, SWEL elevations typically vary from about 11.2 to 11.3 ft NAVD88 from north to south along the project, respectively, which is consistent with the 100-year SWEL variation from the preliminary RAMPP study. Given the close comparison, this storm was used for the model for preliminary design assessments. A constant SWEL of 11.3 ft NAVD88 was used for the transect analysis for determination of wave runup and overtopping. The RAMPP determined SWEL values were also used for the 10-year, 50-year and 500-year return periods. For reference, the 10, 50 and 500-year SWEL are 6.9 ft, 9.9 ft and 14.9 ft NAVD88, respectively at FEMA transect NY-18.

In summary, the procedures for the identification of a coastal storm event for the 100-year SWEL were based on the following:

- FEMA flood study (RAMPP, 2014) at South Battery Park City
- A previous storm model simulation from the preliminary FEMA FIS that generates water elevations similar to the 100-year return period
- wind and pressure fields for the identified storm event were extracted, and
- a simulation of storm surge was performed using the driving forces extracted from the identified storm, with and without sea level rise added to the water level.

### 3.2 Sea Level Rise

Long-term sea-level rise (SLR) predictions produced by different agencies including NOAA, USACE, and the New York City Panel on Climate Change (NPCC) were reviewed. There is a significant variance between different studies with varying uncertainties between low and high confidence level estimates.

Based on the model projection from NPCC, the NYS Department of Environmental Conservation has compiled likely values for the New York region under various projections from low to high

(<https://www.dec.ny.gov/regulations/103877.html>), as listed in Table 3-1.

**Table 3-1 Sea Level Rise Projections for New York City**

<b>Time Interval</b>	<b>Low Projection [inches]</b>	<b>Low Medium Projection [inches]</b>	<b>Medium Projection [inches]</b>	<b>High Medium Projection [inches]</b>	<b>High Projection [inches]</b>
2020s	2	4	6	8	10
2050s	8	11	16	21	30
2080s	13	18	29	39	58
2100s	15	22	36	50	75

In the design phase of this project, the NPCC sea level rise (SLR) of 30 inches (2.5 feet) for the year 2050s with 90th percentile (High Projection from Table 3-1) was used.

### 3.3 Coastal Flooding due to Coastal Storm Surges without Project

Simulation of coastal flooding due to coastal storm surge only, with and without 2.5 feet 2050s SLR, was performed for the existing without project conditions. These simulations show potential flood paths from the SBPC shoreline. The flood maps for the 100-year coastal storm stillwater elevation (wave effect not included), without SLR and with SLR in 2050s are shown in Figure 3-1 and Figure 3-2, respectively. It is clear that without any flood countermeasures, the project site will be inundated under 100-year storm even without SLR.

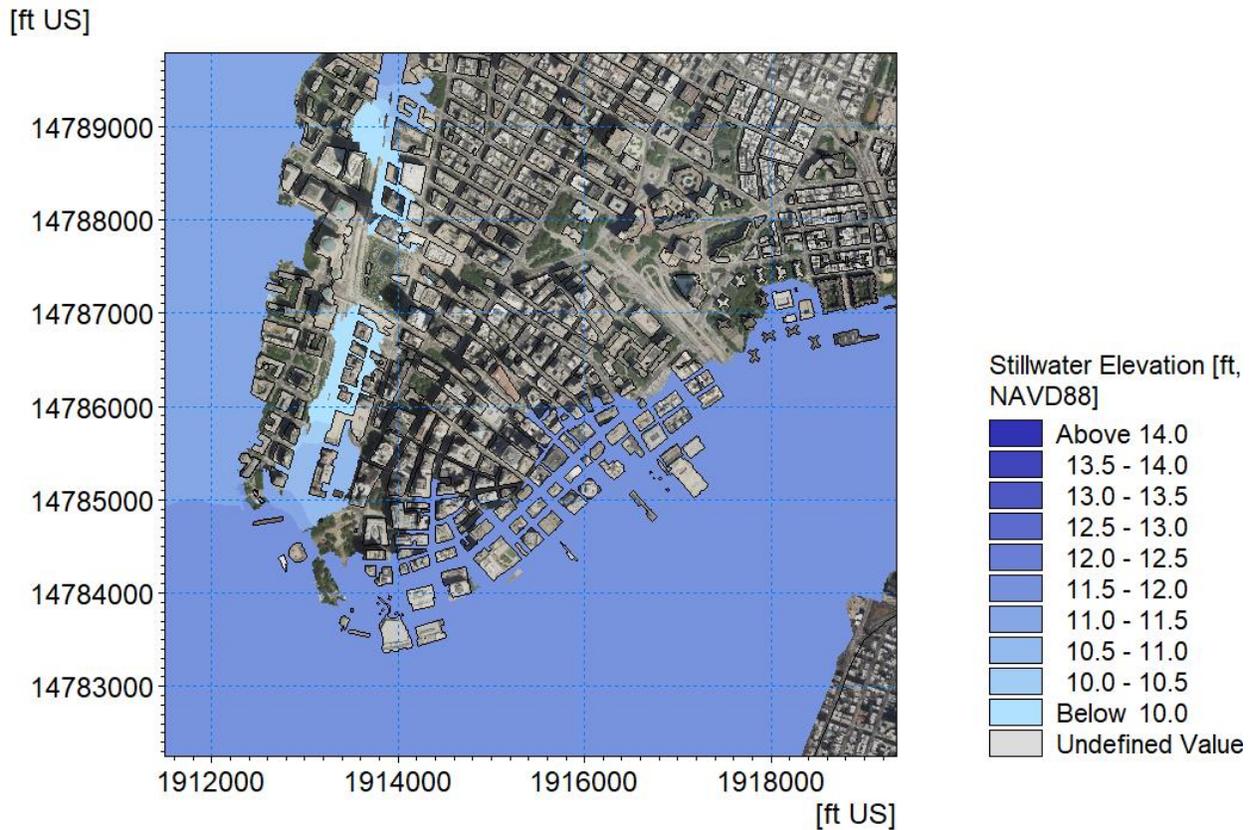
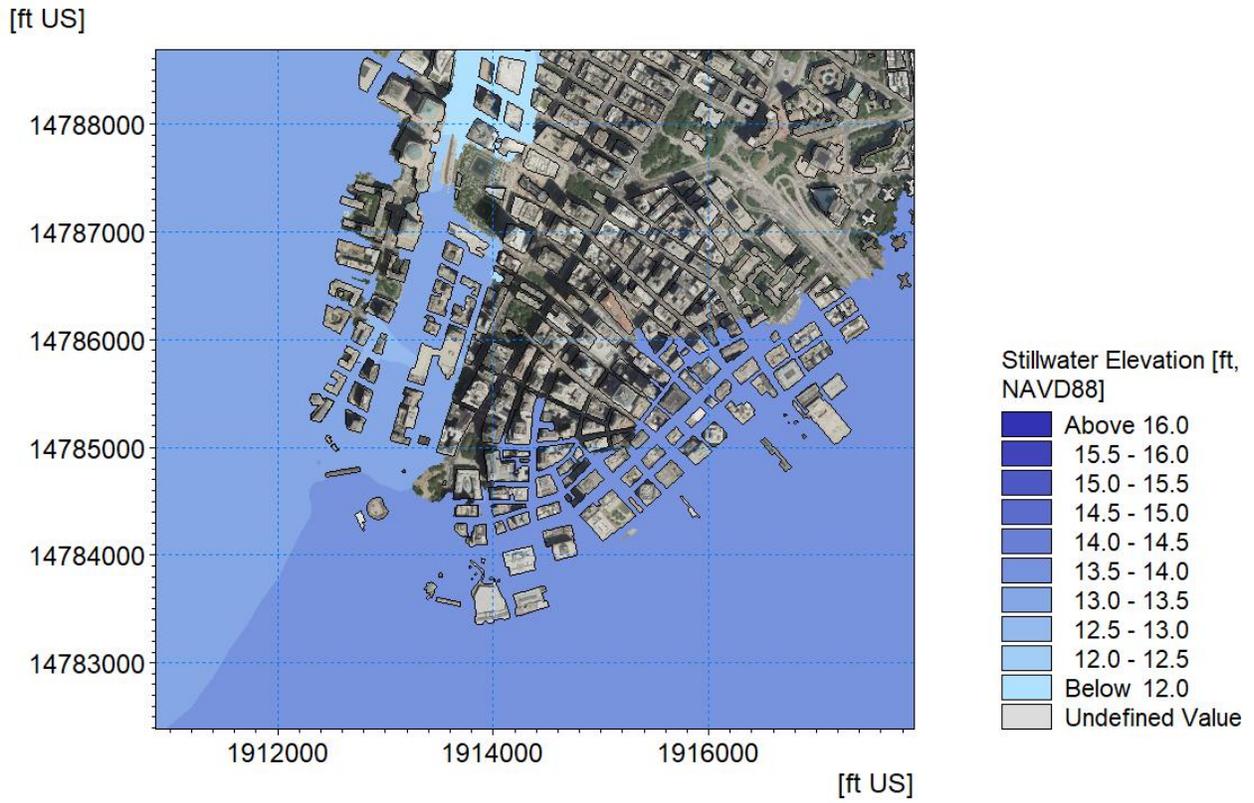


Figure 3-1 100-Year Storm Flood Maximum Stillwater Level for Project Area, without SLR, without project.



**Figure 3-2 100-Year Storm Flood Maximum Stillwater Level for Project Area, with 2050s SLR, without project.**

## 4.0 COASTAL FLOOD ASSESSMENT OF PROPOSED RESISTANT ALIGNMENT

### 4.1 Proposed Flood Resistant Alignment

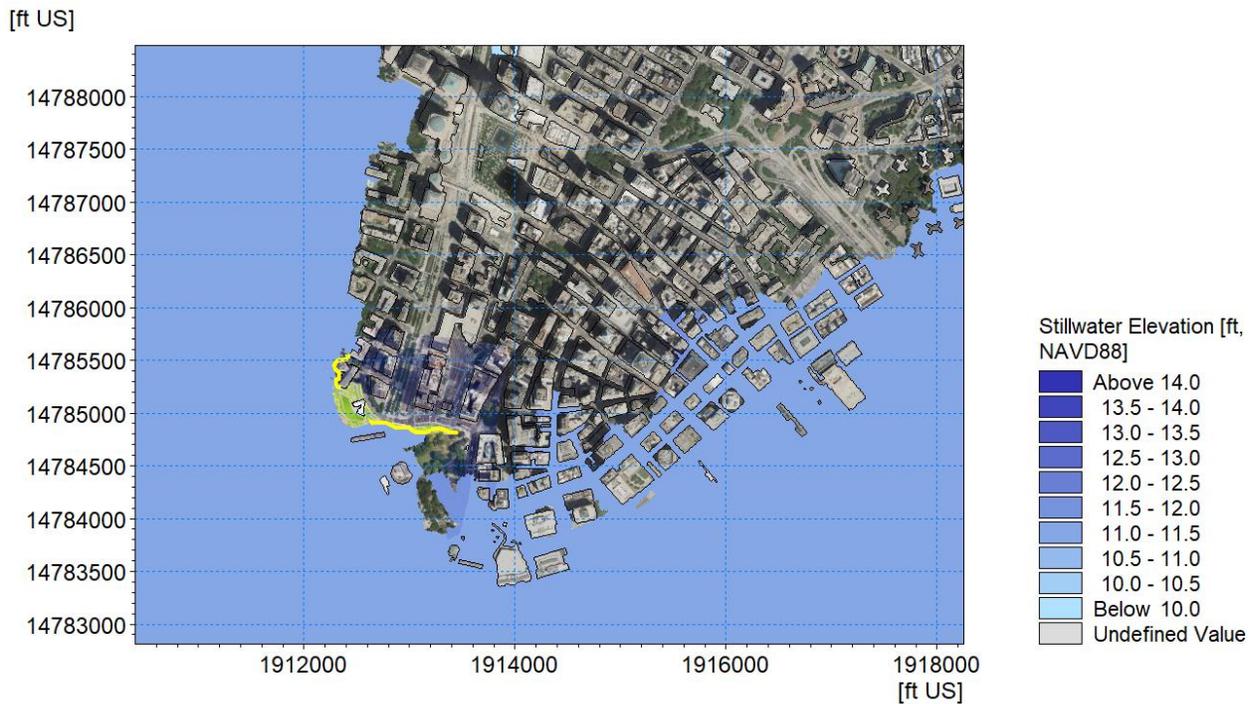
The flood resistant alignment shown in Figure 4-1, which includes flood walls (red line) and raised landscape features, was proposed for the flood resiliency assessment for this project. Note the dashed red line indicates the location of a floodwall that is covered by a sloped fill landscape feature. Note that this study does not take into consideration the western floodwall proposed for the West Battery Park City Resiliency (WBPC) project located to the north of SBPC project.



**Figure 4-1 Proposed Flood Resistant Alignments. Solid red lines represent vertical walls or barriers. The dashed red line is the location of a floodwall that is that is covered by a sloped fill.**

## 4.2 Coastal Flooding due to Coastal Storm Surges (without SLR)

Simulation of coastal flooding due to 100-year coastal storm surge with the proposed flood resistant alignment was performed. The flood map for the 100-year coastal storms (wave effect not included) with the proposed flood resistant alignment using the MIKE 21 HD model is shown in Figure 4-2. It can be seen from Figure 4-2 that the proposed flood resistant alignment can protect the project site effectively from storm surge. Also, comparing to Figure 3-1, it can be observed that the presence of the proposed flood resistant alignment does not create any additional flood impacts to adjacent areas, with respect to the stillwater elevation.

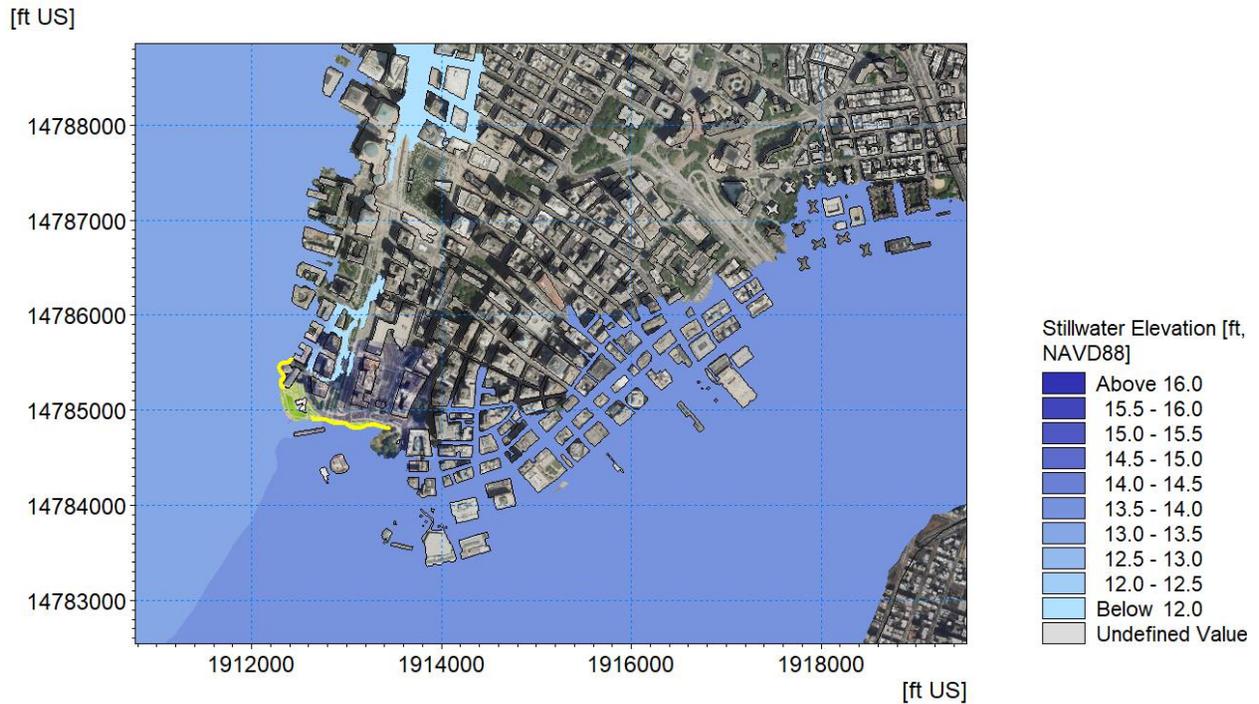


**Figure 4-2 100-Year Coastal Stillwater Elevation Map (without SLR) with the Proposed Flood Resistant Alignment (yellow)**

## 4.3 Coastal Flooding due to Coastal Storm Surges (with SLR)

Simulation of coastal flooding due to 100-year coastal storm surge and SLR in the 2050s with the proposed flood resistant alignment was performed. The flood map for the 100-year coastal storms (wave effect not included) and 2050s SLR with the proposed flood alignment using the MIKE 21 HD model is shown in Figure 4-3 (scenario with no western floodwall proposed for the WBPC project implemented). The proposed flood resistant alignment can prevent flooding of the project site, although flooding through the streets north of the project site (WBPC area) can also be observed. Also, comparing to Figure 3-2, it

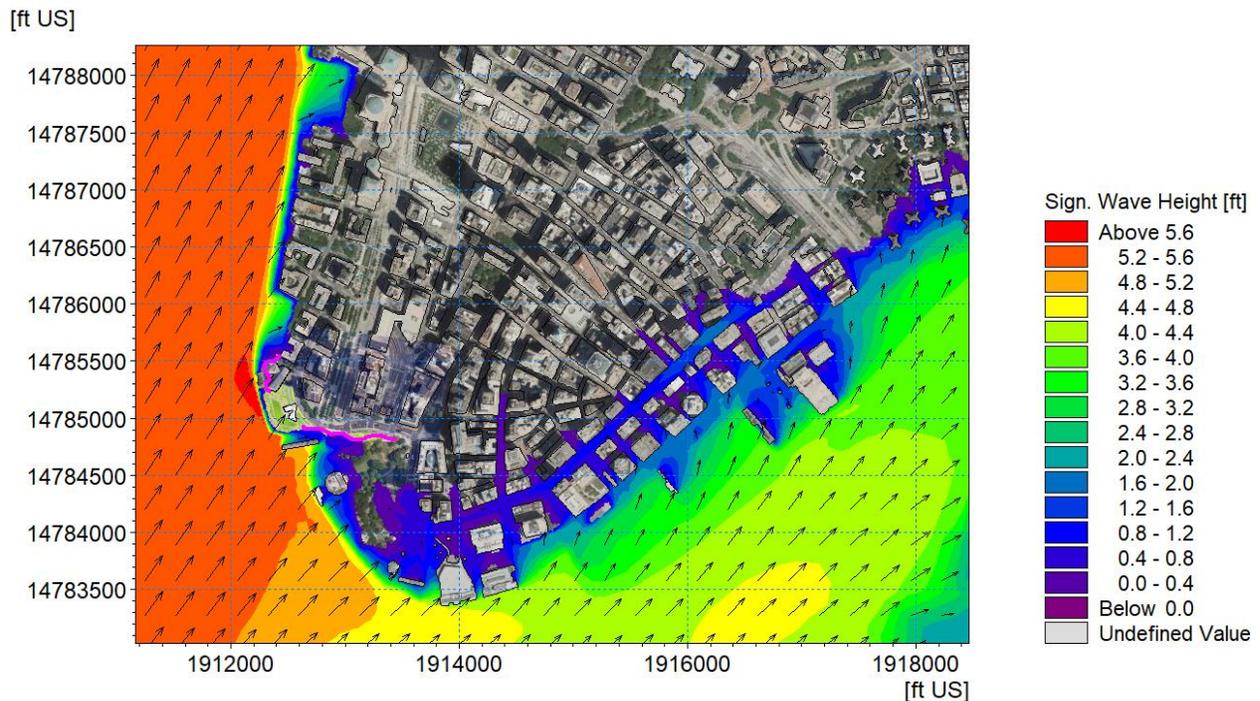
can be observed that the presence of the proposed flood resistant alignment does not create any additional flood impacts to adjacent areas, with respect to the Stillwater elevation.



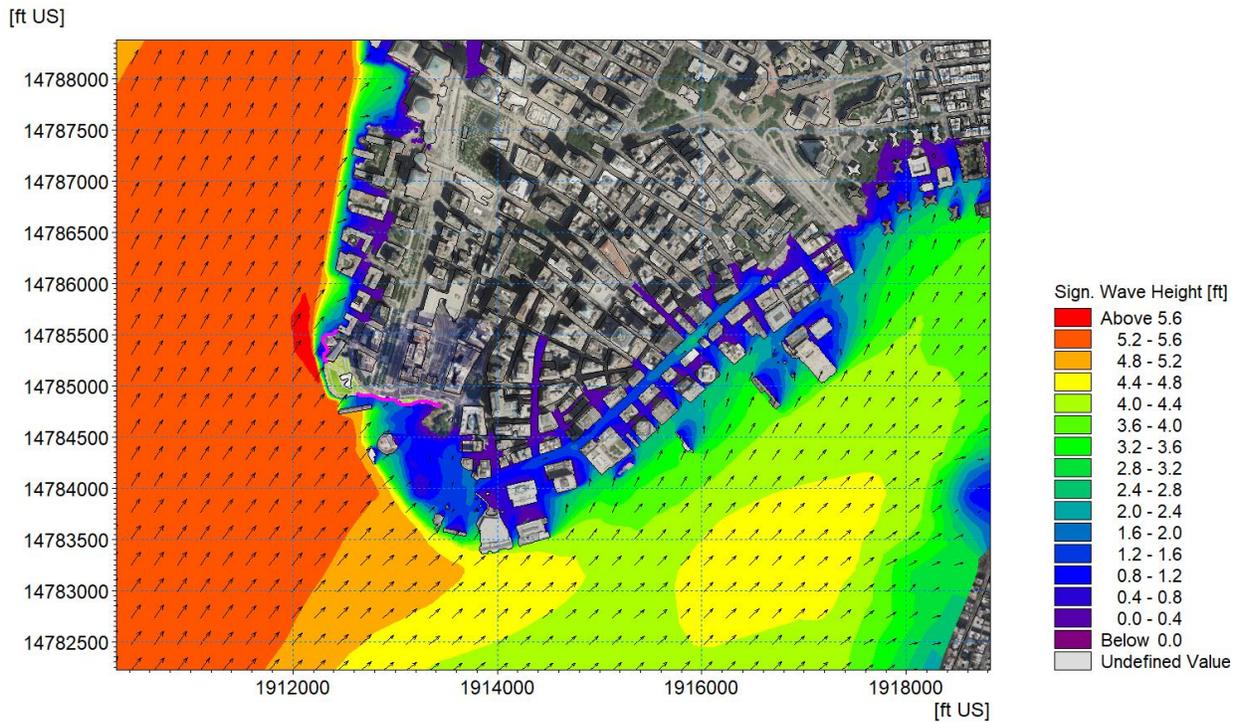
**Figure 4-3 100-Year Coastal Stillwater Elevation Map (with SLR) with the Proposed Flood Resistant Alignment (Scenario with no floodwall proposed for the WBPC Project Implemented)**

#### 4.4 Design Wave Condition

A good understanding of the site-specific storm wave conditions is essential for both the design of the proposed flood resistant alignment and the application of FEMA accreditation of structures and eventual changes to the flood mapping. The MIKE 21 SW model and the MIKE 3 model were used to simulate the wave conditions near the proposed flood resistant alignment. A screenshot of the MIKE 21 SW model simulated wave field under 100-year storm and the proposed flood resistant alignment is shown in Figure 4-4, while the MIKE 21 SW model simulated wave field under 100-year storm and 2050s SLR and the proposed flood resistant alignment is shown in Figure 4-5. Tests of wind from different directions showed that wind from the southwest will generate the most severe wave condition at most locations near the project site



**Figure 4-4 Screenshot of the MIKE 21 SW Model Simulated Wave Field under 100-year Storm (no SLR) with the Proposed Flood Resistant Alignment, Wind Direction from 220 degree to North**

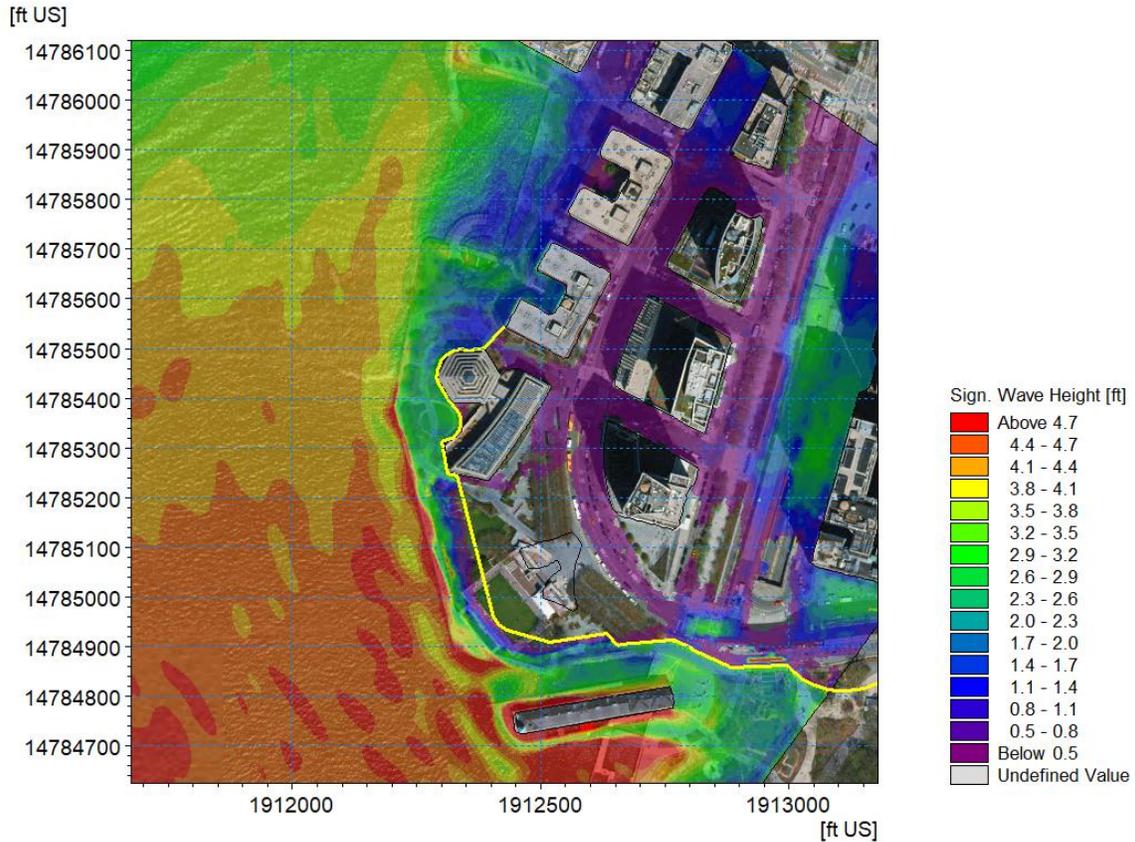


**Figure 4-5 Screenshot of the MIKE 21 SW Model Simulated Wave Field under 100-year Storm and 2050s SLR with the Proposed Flood Resistant Alignment, Wind Direction from 220 degree to North**

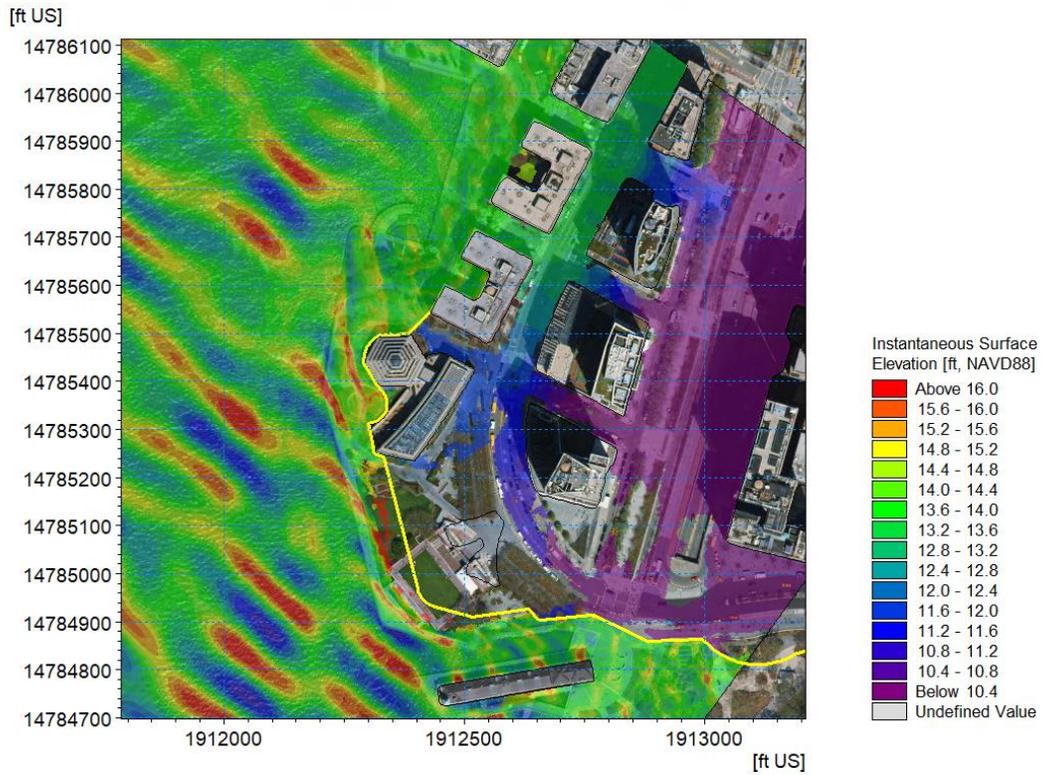
Besides the MIKE 21 SW model, the MIKE 3 wave model was also used to provide additional detailed wave information at the project site, to inform preliminary design, especially to address wave runup and overtopping. Wave parameters describing the incident waves at the southwest boundary of MIKE 3 were extracted from the results of the MIKE 21 SW model simulation of 100-year wave condition under 100-year storm surge and 2050s SLR and applied as inputs into the wave generation routine internal to MIKE 3, to produce irregular waves based on a JONSWAP spectrum. A water level equal to the sum of 100-year SWEL and 2050s SLR was applied as the initial water level. The simulation was run for 20 minutes to establish a fully developed wave field within the model area.

Different wave directions were tested with MIKE 21 SW, and the results of waves coming from southwest (220 degrees), which poses the biggest threat to the resistant alignment, was modeled with MIKE 3, and are presented. The scenario shown here is with no flood wall implemented on the west side. Also, the mesh elevations were based on earlier phase of the project design, and some floodwall design elevations have been raised since these simulations were made. This is especially the case for the barrier just to the north of the Museum of Jewish Heritage, where the model has the barrier elevation at +15.5 ft, NAVD88 from preliminary design phase, but it has been more recently raised to +18.0 ft, NAVD88. Figure 4-6 and Figure 4-7 show the distribution of significant wave height and maximum water surface elevation (wave crest elevation) under 100-year storm stillwater elevation, 2050s SLR, and 100-year

wave condition with the proposed flood resistant alignment. A 3D view of the instantaneous wave field is shown in Figure 4-8.



**Figure 4-6 MIKE 3 Wave Model Simulated 100-year Wave Condition under 100-year Storm Surge Peak and 2050s SLR with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side)**



**Figure 4-7 MIKE 3 Wave Model Simulated Maximum Water Surface Elevation (Wave Crest Elevation) under 100-year Storm Surge Peak, 2050s SLR, and 100-year Wave Condition with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side)**



**Figure 4-8 3D Snapshot of MIKE 3 Wave Model simulated 100-year Wave Field under 100-year Storm Surge Peak and 2050s SLR with the Proposed Flood Resistant Alignment (Scenario with no Flood Wall Implemented on the West Battery Park City side)**

#### 4.5 Design Wave Condition along Proposed Flood Resistant Alignment

Figure 4-9 provides reference to various features relevant to the analysis of wave conditions along the project, especially for the calculation of the wave runup and overtopping using EurOtop. Zones generally delineate common flood protection type or change in elevation of the top of barrier. Sections are typical cross-sections where EurOtop analysis was performed. At each section the terrain is analyzed for the foreshore slope, the structure slope and elevation at the toe of the structure. The toe location establishes where wave parameters are extracted from the MIKE 21 SW model for the calculation. The purple dots indicate the location of the extraction of wave conditions at the toe of structure. An exception to this is in Zone III. In Zone III (Section 2, 1, and 0), there is a sloped fill backed by a 19'-10" floodwall. The floodwall is buried below the top of the sloped fill. For analysis in Zone III, two conditions are analyzed. The first case is as a slope based on the project design terrain assuming no erosion, and a second case where it is assumed the seaward fill is fully eroded to the existing grade, and only the floodwall remains. At all other Sections in all other Zones, the analysis is based on a vertical wall calculation. Other main assumptions used for the EurOtop calculations include a 100-year SWEL level of 11.3 ft, NAVD88 at all sections, based on the preliminary FEMA FIS reported value. Also, deepwater significant wave heights and peak spectral wave periods were applied from the preliminary FEMA FIS WHAFIS analysis, where significant wave heights vary from about 5.01 to 5.13 feet, and peak wave periods vary from about 5.16 to 5.71 seconds.



Figure 4-9 Sketch of Zone and Section Locations along the Proposed Flood Resistant Alignment

#### **4.6 Wave Runup and Overtopping - Transect Based (EurOtop)**

Table 4-1 and Table 4-2 provide the main runup and overtopping EurOtop inputs parameters and calculated values for the no SLR and 2050s SLR case, respectively. The table also includes the currently proposed floodwall elevations and calculations of freeboard. Note, the first nine rows are calculations for a vertical wall, and the last three rows are for a slope, at Section 2, 1 and 0 in Zone III, respectively.

Table 4-1 is useful for evaluating the criteria for FEMA accreditation of coastal structures for the no SLR condition. The Total Water Level +1 foot freeboard calculation can be compared to the structure height to observe that the freeboard requirement for wave runup is met in all cases. Where freeboard criteria is met for runup, the wave overtopping is zero. The freeboard criteria for +2 feet of freeboard above the stillwater level is met at all cross sections. Table 4-2 shows calculations for the future 2050s SLR case, showing a number of the sections will experience some limited amount of overtopping during the peak of a 100-year event, but well below the 0.03 cfs/ft criteria (USACE, 2007) required to meet floodwall design requirements for overtopping and for interior drainage considerations. The 0.03 cfs/ft criteria is for a wall with backside protection with grass cover based on the average overtopping rate.

**Table 4-1 Wave Runup and Overtopping under the 100-year Storm Condition with no SLR**

			1% SWEL	Elevation at Toe	Depth at Toe	Hm0, deepwater	Tp, deepwater	MIKE 21 SW Hm0 at Toe	Floodwall Elevation	Slope	Max Runup	Overtopping, q	Total Water Elevation	Total Water Elevation + 1	SWEL + 2
Type	Zone	Section	(ft, NAVD)	(ft, NAVD)	(ft)	(ft)	(sec)	(ft)	(ft, NAVD)	()	(ft)	(cfs/ft)	(ft)	(ft)	(ft)
Wall	Zone I	Section 5	11.3	11.0	0.3	5.07	5.55	0.2	18.0	-	0.4	0.000	11.7	12.7	13.30
Wall	Zone II	Section 4	11.3	11.0	0.3	5.08	5.50	0.0	18.0	-	0.0	0.000	11.3	12.3	13.30
Wall	Zone II	Section 3	11.3	11.0	0.3	5.08	5.36	0.0	18.0	-	0.0	0.000	11.3	12.3	13.30
Wall	Zone III	Section 2	11.3	11.4	0.0	5.11	5.36	0.0	19.8	-	0.0	0.000	11.3	12.3	13.30
Wall	Zone III	Section 1	11.3	11.3	0.0	5.12	5.36	0.0	19.8	-	0.0	0.000	11.3	12.3	13.30
Wall	Zone III	Section 0	11.3	10.3	1.0	5.12	5.36	0.0	19.8	-	0.0	0.000	11.3	12.3	13.30
Wall	Zone IV	Section -0.5	11.3	9.5	1.8	5.12	5.36	0.6	18.5	-	1.3	0.000	12.6	13.6	13.30
Wall	Zone V	Section -1.0	11.3	10.0	1.3	5.13	5.36	0.1	18.5	-	0.2	0.000	11.5	12.5	13.30
Wall	Zone VI	Section -2.0	11.3	10.0	1.3	5.01	5.17	0.8	18.5	-	1.8	0.000	13.1	14.1	13.30
Slope	Zone III	Section 2	11.3	9.5	1.8	5.11	5.36	1.2	19.8	0.19	2.5	0.000	13.8	14.8	13.30
Slope	Zone III	Section 1	11.3	9.5	1.8	5.12	5.36	1.7	19.8	0.22	4.1	0.000	15.4	16.4	13.30
Slope	Zone III	Section 0	11.3	9.6	1.7	5.12	5.36	0.0	19.8	0.20	0.0	0.000	11.3	12.3	13.30

**Table 4-2 Wave Runup and Overtopping under the 100-year Storm Condition with 2050 SLR**

			1% SWEL	Elevation at Toe	Depth at Toe	Hm0, deepwater	Tp, deepwater	MIKE 21 SW Hm0 at Toe	Floodwall Elevation	Slope	Max Runup	Overtopping, q	Total Water Elevation	Total Water Elevation + 1	SWEL+ 2
Type	Zone	Section	(ft, NAVD)	(ft, NAVD)	(ft)	(ft)	(sec)	(ft)	(ft, NAVD)	()	(ft)	(cfs/ft)	(ft)	(ft)	(ft)
Wall	Zone I	Section 5	13.8	11.0	2.9	5.07	5.55	1.5	18.0	-	3.6	0.0039	17.4	18.4	15.80
Wall	Zone II	Section 4	13.8	11.0	2.8	5.08	5.50	1.9	18.0	-	4.4	0.0111	18.2	19.2	15.80
Wall	Zone II	Section 3	13.8	11.0	2.8	5.08	5.36	1.0	18.0	-	2.2	0.0003	16.0	17.0	15.80
Wall	Zone III	Section 2	13.8	11.0	2.8	5.11	5.36	2.0	19.8	-	4.7	0.0049	18.5	19.5	15.80
Wall	Zone III	Section 1	13.8	11.3	2.5	5.12	5.36	2.0	19.8	-	4.7	0.0056	18.5	19.5	15.80
Wall	Zone III	Section 0	13.8	10.3	3.5	5.12	5.36	0.6	19.8	-	1.4	0.0000	15.2	16.2	15.80
Wall	Zone IV	Section -0.5	13.8	9.5	4.3	5.12	5.36	1.5	18.5	-	3.6	0.0022	17.4	18.4	15.80
Wall	Zone V	Section -1.0	13.8	10.0	3.8	5.13	5.36	1.8	18.5	-	4.2	0.0053	18.0	19.0	15.80
Wall	Zone VI	Section -2.0	13.8	10.0	3.8	5.01	5.17	2.0	18.5	-	4.6	0.0077	18.4	19.4	15.80
Slope	Zone III	Section 2	13.8	9.5	4.3	5.11	5.36	3.1	19.8	0.19	6.4	0.0003	20.3	21.3	15.80
Slope	Zone III	Section 1	13.8	9.5	4.3	5.12	5.36	3.5	19.8	0.22	8.5	0.0050	22.4	23.4	15.80
Slope	Zone III	Section 0	13.8	9.6	4.2	5.12	5.36	0.7	19.8	0.20	1.6	0.0000	15.4	16.4	15.80

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the coastal flood assessment for the existing conditions and proposed flood resistant alignments, the major conclusions are summarized as follows:

- For the existing conditions, the Project Area is vulnerable to coastal storms for the 100-year storm with or without SLR.
- With the proposed floodwall elevations, no wave overtopping will occur, and wave runup freeboard requirements will be met for the no SLR condition for the 100-year storm.
- For the proposed floodwall elevations, and the 2050s SLR condition, some overtopping of structures will occur within the project, but will be below the 0.03 cfs/ft requirement for the 100-year flood event.
- While the 100-year storm is used as the design storm, considering the vulnerability of the project site, a 500-year storm should be simulated to assess the extent of possible flooding for this rare event.
- Uncertainty of flooding coming from the area west of the project site (West Battery Park City area) needs to be realized given the absence of flood countermeasures there.
- No impact due to the proposed flood resistant structure to stillwater elevations on adjacent properties was observed from the modeling. Wave impacts due to the structure on adjacent properties was not analyzed in the current scope of work.

---

## 6.0 REFERENCES

EurOtop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., [www.overtopping-manual.com](http://www.overtopping-manual.com)

FEMA Modeling Task Force (MOTF), 2013. Hurricane Sandy Impact Analysis (<https://www.arcgis.com/home/item.html?id=3a5c59699d86453a89f590171a10e9b5>).

FEMA, 2013. Preliminary Flood Insurance Study - City of New York, New York.

FEMA, 2014. Region II Coastal Analysis and Mapping (<http://www.region2coastal.com/view-flood-maps-data/>).

RAMPP 2014, 2014. Region II Coastal Storm Surge Study Overview, FEMA TO HSFE02-09-J-001.

RAMPP 2014a, 2014. Region II Storm Surge Project – Spatially Varying Nodal Attribute Parameters, FEMA TO HSFE02-09-J-001.

RAMPP 2014d, 2014. Region II Storm Surge Project - Model Calibration and Validation, FEMA TO HSFE02-09-J-001.

RAMPP 2014e (Oceanweather, Inc.), 2014. Region II Storm Surge Project - Development of Wind and Pressure Forcing in Tropical and Extratropical Storms, FEMA TO HSFE02-09-J-001.

U.S. Army Corps of Engineers (2002). Coastal Engineering Manual, 1110-2-1100.

U.S. Army Corps of Engineers (2007). Elevations for Design of Hurricane Protection Levees and Structures. Lake Pontchartrain, Louisiana and Vicinity, Hurricane Protection Project, West Bank and Vicinity, Hurricane Protection Project. New Orleans District Report. October 9, 2007. Section 1.3, pp 7.